Chapter

Soil Erosion Risk Analysis of a Small Watershed

Galdies Charles, Zammit Amy and Gauci Adam

Abstract

Malta is being rapidly exposed to developmental activities occurring inland and along its coastline, which in turn triggers erosion and flooding in the event of high-intensity rainfall. Most of the rainwater-containing several contaminants from urban and agricultural areas are lost as runoff into the coastal waters, which in turn have adverse environmental and socioeconomic impacts. The extent of soil erosion and runoff can be investigated starting from the watershed basin downhill till coastal waters. This study links the runoff of soil along an ecologically sensitive watershed in Malta with the use of multidisciplinary techniques. These included the estimation of soil erosivity coupled with satellite remote sensing chlorophyll-a (CHLA) and total suspended matter (TSM) in coastal waters adjacent to the mouth of the valley. This represents a novel study for the Maltese islands because it provides a precise map of soil erosion hotspots in the Ramla watershed as high as 30 ton ha^{-1} yr^{-1}. Using three case studies of past torrential rain episodes, the sedimentation process resulted in a 120% and 133% increase in CHLA and TSM levels, respectively, against background levels. This information is vital for proper risk management of ecologically sensitive watershed basins.

Keywords: Malta, RUSLE, chlorophyll-a, total suspended matter, COPERNICUS

1. Introduction

Finely textured sediments originating from upland areas get deposited further down in lowland areas, forming one of the most fundamental earth processes. Sedimentation processes stretch across other disciplines, including soil and plant science, geomorphology, and coastal zone management. Ongoing research in the field of sedimentology is, therefore, very relevant because changes in global sediment transport are being used as a primary form of evidence for the Anthropocene.

Like sedimentation, soil erosion is a dynamic, multistage process involving soil detachment, breakdown, transport, and subsequent deposition that is forced by wind or rain, or through soil-intensive human activities such as farming [1]. Soil erosion can lead to serious loss of topsoil and organic matter, which can lead to reduced vegetation growth and to biodiversity in general [2]. The focus of this chapter is on the multidisciplinary understanding between soil erosion, transport, and its impact within a localized watershed situated in the Maltese islands, using a range of techniques that are highly suited for risk management.

Figure 1.
The Maltese islands show the study area located in Gozo. (Source: OSM & Malta GeoPortal – Planning Authority).

The Maltese islands are located within the central Mediterranean region (**Figure 1**). According to CMIP6 climate models, the projected future climate of the islands is expected to experience a higher frequency of climatic extremes, including prolonged drought conditions and heatwaves, as well as increased frequency of torrential rain that can cause intermittent but significant flooding. The latter may, thus, result in increased mass wasting and related soil erosion, which can negatively affect erosion-vulnerable watersheds that are already significantly impacted by unsustainable and intense anthropogenic influences, including agriculture and associated sediment displacement. Clays and silts from upper parts of watersheds, once suspended in the stream network, can be routed directly to the mouth of the valley, resulting in significant sediment loads in coastal waters, and thus affecting exposed and submerged coastal ecosystems.

Severe rainstorms can have significant short- to long-term impacts on coastal water quality as a result of soil erosion and sedimentation processes both during and after their occurrence, especially if they are well outside historically observed norms. Extreme rainfall events can transport significant amounts of suspended sediment containing a variety of pollutants (such as heavy metals and organic compounds) through watersheds, ending up into coastal waters. Water runoff may also carry sufficiently coarse sediments to block the penetration of light through the water column, and thus be able to impact sensitive benthic flora and fauna. According to Ref. [3], the upper tolerance of total suspended sediments for most aquatic species is 80–100 mg/L, but it can be much less for bottom-dwelling aquatic invertebrates.

For these reasons, it is very important to understand the degree of these processes for eventual management of such risks within important watersheds. Such a study requires an accurate identification of the connectivity between the degree of soil erodibility and the corresponding impact to coastal waters resulting from sedimentation at the local scale. In this chapter, we look at an integrated assessment of sediment dynamics typically triggered by a rainstorm occurring within an important watershed in the Maltese islands, namely the identification of problems having a significantly high degree of soil erodibility, and the estimation of both total suspended matter

(TSM) and chlorophyll-a (CHLA). The morphometrics of the Ramla watershed was derived from a very high-resolution DEM derived using LiDAR, and evaluated in detail. The revised universal soil loss equation (RUSLE) model was used to assess the degree of soil erodibility, while Earth observation technology was used to estimate the impact of surface runoff on coastal water.

2. Case study: The Ramla watershed in Gozo

The Ramla watershed in Gozo is roughly a 6 km^2 catchment area extending from its watershed divide down to the Ramla beach (**Figure 1**). The socioeconomic and environmental importance of this sensitive watershed is based on intensive farming activities [4], the presence of perched aquifers along its slopes (MT015 & MT016. [5]), unique biodiversity [6], and the presence of a NATURA 2000 site [4, 7].

According to Ref. [8], the Ramla watershed has formed through the fragmentation and dislodgment of the upper coralline plateau along the edges of the headlands overlooking, which is being sustained by the erosion of the underlying blue clay strata. The detachment of rock mass of various sizes then continues to fragment and weather into small pieces. Its geomorphology is characterized by somewhat steep relief, with elevations ranging between 120 and 28 m above sea level and an average slope of 18.1%. Its climate features mild, humid winters and hot, dry summers an annual mean air temperature of 18.6°C, and a mean precipitation of 574 mm [9]. The rainfall regime is intermittent with baseflow from October to January.

The Ramla watershed has been much affected by human activities. Agriculture has evidently shaped the watershed into a system of terraced fields that are delineated by rubble walls to define and protect the land parcels (**Figure 2b**). However, the area still continues to show natural depositional features including gullies and rills, as well as its principal watercourse and associated tributaries. The slopes are affected directly by rainfall resulting in surface runoff in the form of stream flow, which at higher slope elevations of the Ramla catchment removes the weathered material of the clay and makes the surface of the slope smoother. Splash erosion can happen when clay particles are moved about by raindrops. This becomes significant over the barren parts of slopes.

2.1 Methodology

2.1.1 Morphometric analysis

National 1 × 1 m DEM derived from LiDAR and 15 cm pixel resolution aerial orthophotographs [10] were used for morphometric analysis in a GIS environment. The terrain analysis approach of SAGA GIS V8.5.1 [11] was used to derive morphometry characteristics of the watershed. A number of specific software tools were used: channels [12], hydrology, and morphometry [12]. These tools extracted the presence of watersheds and sub-watersheds in an automated manner in the form of GIS vector layers. For a proper determination of flow direction and flow accumulation, sinks were identified from the DEM and filled. After the drainage networks were extracted and sub-watersheds were delineated, four sets of morphometric parameters were calculated using the mathematical formulations as described in **Table 1**.

The stream order is the primary step in quantitative interpretations of a drainage network, and the stream number is the number of streams in each order. These two

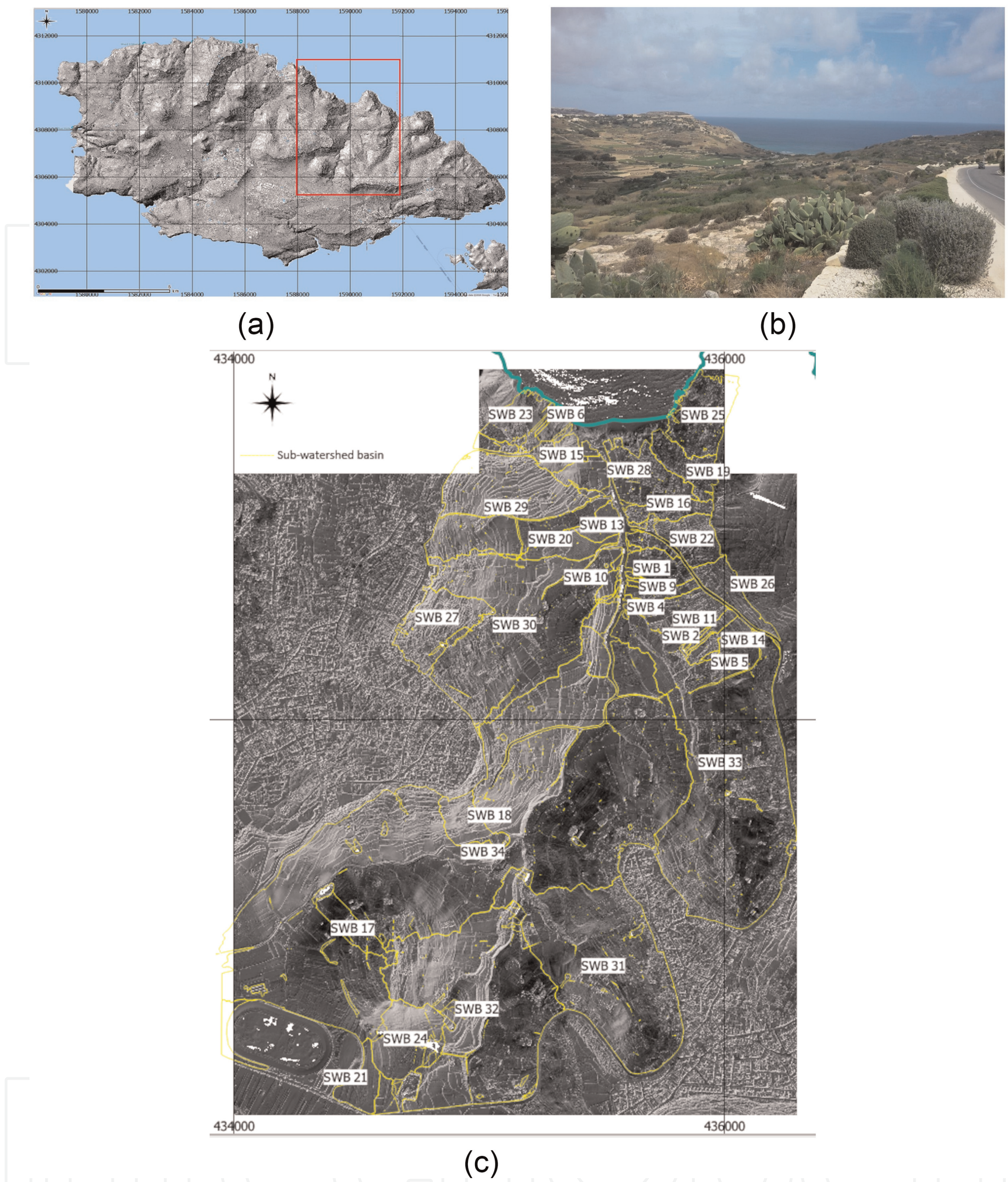

Figure 2.
(a) Topographic relief of the island of Gozo showing the area of interest (inset), (b) onsite agricultural land cover of the watershed taken from south-eastern watershed divide, and (c) analytical Hillshading derived from LiDAR-derived elevation data. (Source: Authors).

No	Parameters	Equation	References
1	Stream order	Hierarchic order	[13, 14]
2	Stream number	$Nu = N1 + N2 + N3 + \ldots Nn = \Sigma N_u$	[13]
3	Stream length	$Lu = L1 + L2 + L3 + \ldots Ln = \Sigma L_u$	[13, 14]
4	Mean stream length	$L_{ms} = Lu/Nu$	[14]
5	Terrain ruggedness index	$TRI=Y[\Sigma(x_{ij}-x_{00})^2]^{1/2}$	[15]

Table 1.
Parameters derived from the morphometric analysis.

parameters produce a geometric relationship that resulted in the calculation of the stream length of the drainage that was based on the surface runoff characteristics of the basin. The total length of individual stream segments of each order was, thus, derived, while the extracted Mean stream length provides information of the drainage size and its contributing basin surface. The terrain ruggedness index (TRI) was also calculated by calculating the sum change in elevation between a grid cell and its eight neighbor grid cells, where x_{ij} is the elevation of each neighbor cell to cell. The watershed basin characteristics, the channel network, and sink route were subsequently derived from the DEM to produce a basin shapefile, along with other shapefiles [12].

2.1.2 Soil erosion

Soil erodibility within the Ramla watershed was estimated using the RUSLE [16]. The soil erodibility was estimated using the following equation:

$$A = R^* \ K^* \ LS^* \ C^* \ P.$$

where A is the estimated soil loss in tons per hectare per year, R is the rainfall erosivity factor, K factor is a measure of soil erodibility, LS is the slope length and steepness factor, C is the cover and management factor, and P is the support practice factor.

2.1.3 Estimation of CHLA and TSM

The derivation of the climatological profile of CHLA and TSM was based on the analysis of 10 years' worth of monthly 300 m MERIS L1B sensor data derived by ENVISAT-1. The observation period ranged between May 17, 2002 until April 8, 2012, and is equivalent to 3614 days for the area of interest (**Figure 3**). The algorithm used to derive CHLA (in $mg.m^{-3}$), and TSM (in $g.m^{-3}$) was based on Case 2 water monitoring [17] with a spatial resolution of 0.3 km/pixel data products. Average concentrations of CHLA were derived using the OC4 algorithm and TSM [18]. The monthly climatological processing of the CHLA and TSM was conducted using MATLAB coding.

For this case study, near real-time, high-resolution COPERNICUS Sentinel-2A and 2B (L1C) imagery overpasses were used to derive CHLA and TSM quantitative maps that coincided with the rainstorm events observed between the January 2 and 12, 2021. Prior to processing, images were resampled using Band-2 due to its high spatial resolution (10 m). Salinity and temperature parameters needed for algorithm processing were set to reflect the values observed in Maltese coastal waters based on their monthly averages.

3. Results

3.1 Ramla watershed characteristics

This watershed shows highly interesting features as highlighted by the geomorphometric processing results that exploited the unprecedented spatial resolution provided by the national LiDAR data. **Table 2** shows the morphometric features of all the main hydrological sub-catchments that were derived using GIS-based terrain raster processing (**Figure 2c**). These features include the minimum, maximum, and

	Strahler stream number					Total stream length (m)					Mean stream length (m)				
Sub-Watershed basin	Order 1	Order 2	Order 3	Order 4	Order 5	Order 1	Order 2	Order 3	Order 4	Order 5	Order 1	Order 2	Order 3	Order 4	Order 5
1	1	0	0	0	0	54.4	—	—	—	—	54.4	0.0	0.0	0.0	0.0
2	2	2	0	0	0	87.5	82.9	—	—	—	43.7	41.5	—	—	—
3	0	0	0	0	0	—	—	—	—	—	0.0	0.0	0.0	0.0	0.0
4	0	0	1	0	0	—	—	1.0	—	—	—	—	64.8	—	—
5	2	1	0	0	0	31.0	30.7	—	—	—	15.5	30.7	—	—	—
6	2	0	0	0	0	174.7	—	—	—	—	87.4	—	—	—	—
8	0	0	0	0	0	—	—	—	—	—	0.0	0.0	0.0	0.0	0.0
9	2	1	2	0	0	144.4	25.1	41.3	—	—	72.2	25.1	20.6	—	—
10	1	1	1	0	0	23.0	29.1	39.0	—	—	23.0	29.1	39.0	—	—
12	5	2	2	0	0	172.1	102.6	38.0	—	—	34.4	51.3	19.0	—	—
13	0	0	0	0	0	—	—	—	—	—	0.0	0.0	0.0	0.0	0.0
14	13	5	0	0	0	430.8	296.0	—	—	—	33.1	59.2	—	—	—
15	10	4	6	0	0	494.4	220.5	128.4	—	—	49.4	55.1	21.4	—	—
16	9	6	1	0	0	219.3	296.5	12.1	—	—	24.4	49.4	12.1	—	—
17	13	3	8	0	0	477.1	92.2	540.8	—	—	36.7	30.7	67.6	—	—
18	20	17	0	0	0	646.6	966.0	—	—	—	32.3	56.8	—	—	—
19	19	13	1	0	0	1221.4	482.2	28.0	—	—	64.3	37.1	28.0	—	—
20	18	11	6	3	0	878.7	385.7	264.3	191.7	—	48.8	35.1	44.0	63.9	—
21	28	14	4	6	0	1446.3	815.0	147.9	262.0	—	51.7	58.2	37.0	43.7	—
22	26	14	6	0	0	1157.1	785.5	406.5	—	—	44.5	56.1	67.7	—	—
23	24	13	6	1	0	1039.4	521.7	144.3	165.8	0.0	43.3	40.1	24.1	165.8	—

	Strahler stream number					Total stream length (m)					Mean stream length (m)				
Sub-Watershed basin	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**	**Order 1**	**Order 2**	**Order 3**	**Order 4**	**Order 5**
24	37	20	11	8	1	1434.5	968.2	327.9	319.9	54.7	38.8	48.4	29.8	40.0	54.7
25	42	22	6	0	0	1957.4	986.4	310.1	—	—	46.6	44.8	51.7	—	—
26	43	26	8	1	0	2162.4	678.8	162.7	30.6	—	50.3	26.1	20.3	30.6	—
27	54	36	12	0	0	1737.0	1511.4	403.8	—	—	32.2	42.0	33.6	—	—
28	39	26	7	0	0	2306.6	1892.7	374.9	—	—	59.1	72.8	53.6	—	—
29	50	23	19	0	9	1727.8	892.6	700.2	—	470.5	34.6	38.8	36.9	—	52.3
30	65	36	23	4	0	2132.0	1364.0	864.5	94.2	—	32.8	37.9	37.6	23.5	—
31	150	68	23	27	10	7514.4	2938.0	647.7	985.1	134.8	50.1	43.2	28.2	36.5	13.5
32	245	130	51	38	17	11427.3	5370.5	2209.2	1523.4	432.1	46.6	41.3	43.3	40.1	25.4
33	241	131	49	23	45	10820.9	5925.0	1874.3	904.2	818.6	44.9	45.2	38.3	39.3	18.2
34	283	135	68	36	19	11767.1	4899.2	2542.7	982.8	353.7	41.6	36.3	37.4	27.3	18.6

Table 2.
Calculated stream order, stream number, and stream lengths of the hydrological sub-watershed basins identified within the Ramla watershed.

Figure 3.
SENTINEL2-A image of the Ramla valley mouth, sandy beach, and adjacent coastal waters (Source: COPERNICUS).

average elevation of each sub-catchment basin together with the Strahler stream number and their lengths [13].

Detailed morphometric analysis shows that the largest sub-watershed basin is around 110 ha (SWB 3, **Figure 2c**). The mapping of the 4th and 5th stream order categories found in the Ramla watershed area is shown in **Figure 2b**. According to **Table 2**, the longest water channels belong to stream order 2 followed by stream order 1, with a total of 2760 and 1427, respectively. The drainage pattern is tightly linked to a landform, where rocks are flat-lying and preferential zones of structural weakness are minimal.

This integrated analysis points to a sub-watershed structure that is the direct result of an underlying lithology with a hydrology that is a direct function of the geomorphology and topography, including that which is artificially induced. Results show that stream runoff in the Ramla valley catchment is mainly dominated by SWB 34, 31, 33, and 10. Therefore, these sub-watersheds are deemed to be important from a soil erodibility management point of view.

3.2 Degree of soil erodibility from the Ramla watershed

Soil erodibility within the valley (**Figure 4b**) varies from a low (blue color shading) to a high rate of more than 30 ton ha^{-1} $yr.^{-1}$ (yellow color shading). The RUSLE estimation showed that the area around the in-Nuffara Hill is likely to be most affected by high erosion rates. This is because its slopes consist of fallow fields which lack proper maintenance of rubble walls together with the occurrence of motorcycle off-roading practice, which together are contributing to higher soil erosion. The high slopes along Xaghra (west) and Nadur (east) headlands, which consist of blue clay and also silty soil, also show a high degree of soil erodibility (**Figure 4b**).

The RUSLE estimation of the Ramla watershed shows that its soil erosivity can be generally considered as tolerable (<10 ton ha^{-1} $yr.^{-1}$). The type of land-use land

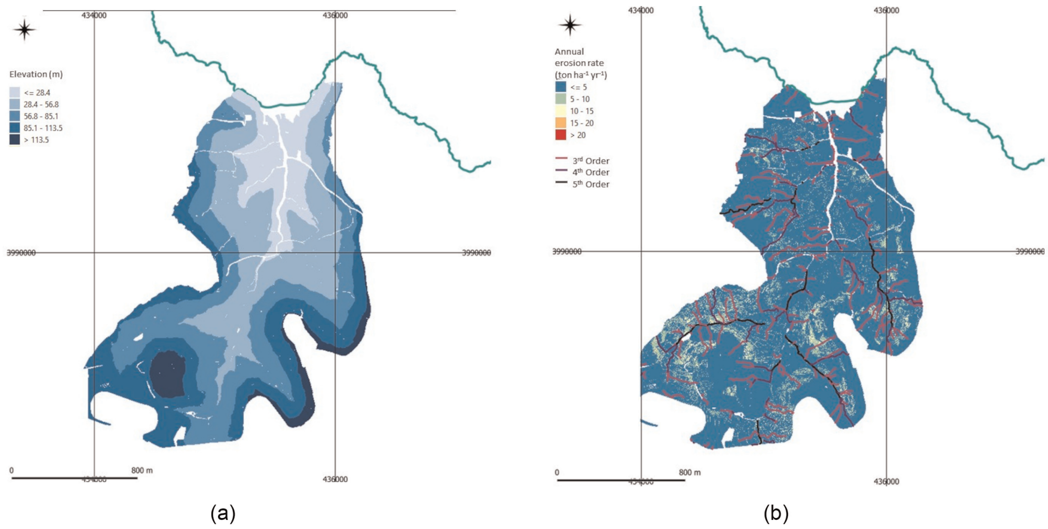

Figure 4.
DEM (a), and RUSLE, showing 3rd-, 4th-, and 5th-order channels derived by this study, leading to the mouth of the valley and into the coastal waters (b).

cover present within the tolerable range is generally characterized by seasonal crops and by a gentle slope gradient that tends to cause reduced runoff velocity. However, at higher slope gradients, one can observe elevated risks of soil erosion (>30 ton ha^{-1} yr.$^{-1}$) associated with the onsite presence of abandoned and/or neglected field terraces having poor vegetation cover. Site investigations also point to a significant collapse of protective barriers within these areas (**Figure 5**).

The terrain ruggedness index (TRI), which is based on the sum change in elevation between a grid cell and its neighboring grid cells of 1 m^2 ground resolution, reveals the distribution of the terrain heterogeneity. The resultant TRI map shows high ruggedness within certain parts of the valley system that are also prone to soil erosivity (**Figure 6b**). The TRI map shows high values to the left of the valley mouth, which incidentally is also associated with a significant degree of erodibility (**Figure 4b**, with areas having a soil erodibility of around 10–15 ton ha^{-1} yr.$^{-1}$) incorporating in it a number of stream channels that head directly toward the coast and therefore, contributing to sediment movement toward this direction. High index values are also

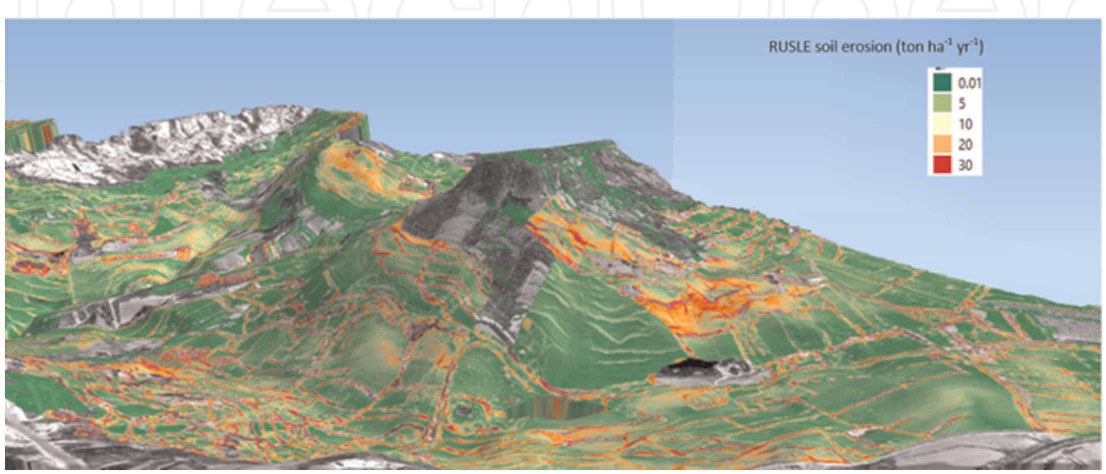

Figure 5.
*High risk of erosion located along the in-Nuffara Hill area (shown in red), which is primarily associated with SWB 34 (**Figure 3c**).*

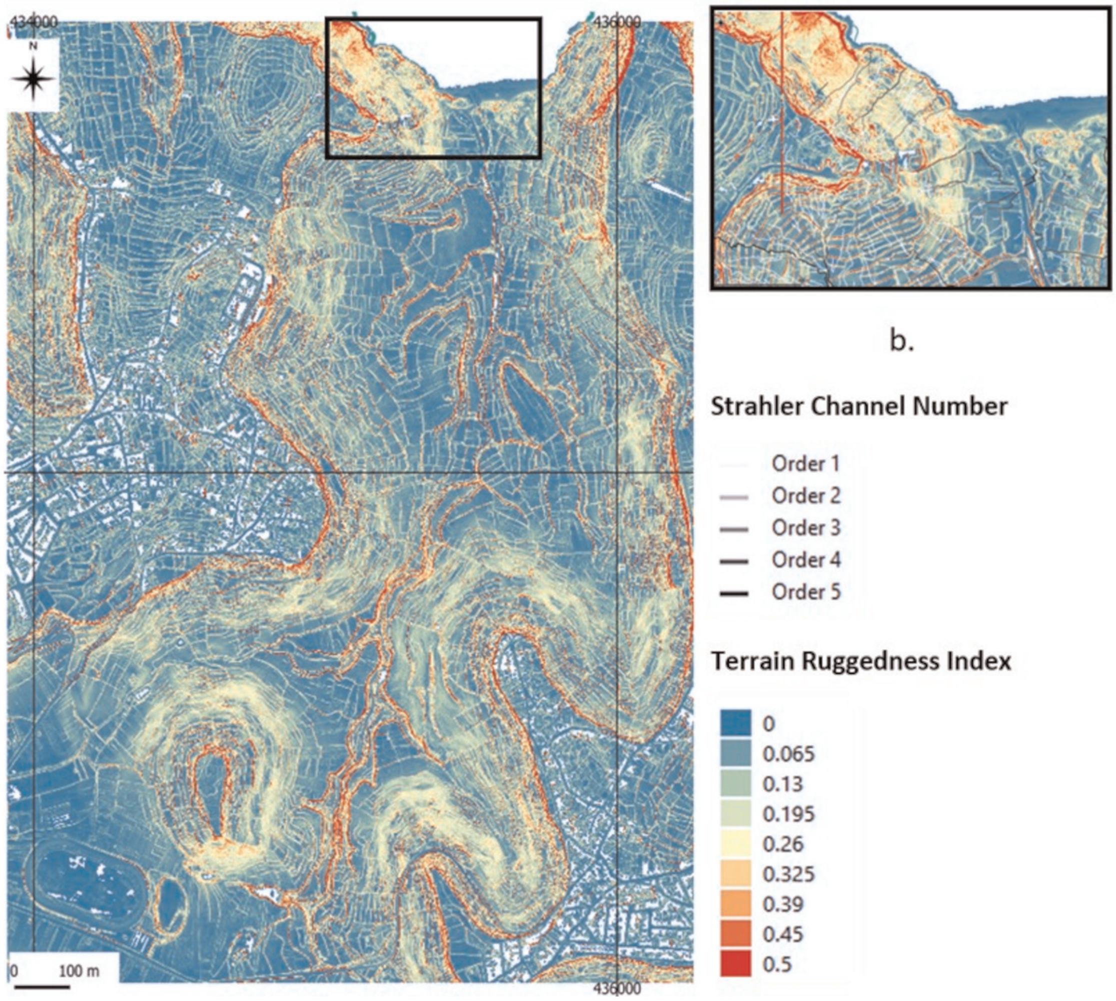

Figure 6.
*Terrain ruggedness index map derived for the Ramla watershed (a). Note the high index value in the inset (b) to the left of the valley mouth associated with significant degree of erodibility (**Figure 4b**, with areas having around 10–15 ton ha^{-1} yr.$^{-1}$) and associated stream channels heading toward the coast.*

found within the southern parts of the Ramla valley associated with the high degree of erosivity surrounding the in-Nuffara Hill (**Figure 5**).

3.3 Risk of sedimentation from the watershed into Ramla coastal waters following soil erosion due to rainstorms

3.3.1 Rainstorm events during January 2021

The daily rainfall amount in mm was obtained from the nearest weather station situated in Gozo (**Table 3**). Winds from the south reached an average speed 25 km/hr.

The computation and mapping of CHLA and TSM are shown in **Figures 7–13**. Histograms for coastal water quality showed that for the first part and end part of the event the CHLA is positively skewed (**Figure 8**), implying that concentrations returned to pre-rainfall conditions. The combined histogram (**Figure 9**) expressed the variation of concentrations before and after the rainstorm, which coincides with the climatological extent obtained for January based on MERIS data (**Figure 10**).

The TSM concentration showed a slight increase toward higher levels on the second date (**Figure 11**). However, the shift was less evident than for CHLA as frequency values remained positively skewed throughout the analysis (**Figure 12**). A slight increase in TSM can be seen for January 7th, implying that TSM concentrations had increased, likely due to sediment runoff from Ramla valley system (**Figure 13**).

Climatological analysis for the Ramla coastal waters shows that rainstorm events are highly likely to increase the water levels of CHLA and TSM levels since these two parameters were observed to peak during the wetter months. The near real-time high-resolution imagery confirmed this observation (**Table 4**) in a way that CHLA and TSM levels have increased after the rainfall event and decreased after a few days. This also links to the impact of rainfall on the sedimentation process within the Ramla watershed. According to **Table 4**, during the January rainstorm event, the sedimentation and associated nutrients ending up in adjacent coastal waters found next to the mouth of the watershed resulted in a 120% and 133% increase in CHLA and TSM levels, respectively, against background levels.

Date of rainstorm event	Rainfall (mm)
02/01/2021	8.5
03/01/2021	4.3
04/01/2021	3.2
07/01/2021	0.0
08/01/2021	0.3
12/01/2021	2.3

Table 3.
Rainfall (mm) during the rainstorm of January 2021.

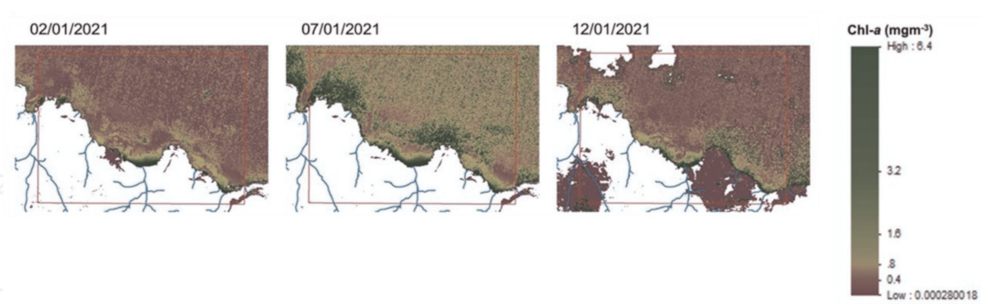

Figure 7.
CHLA concentration (mg.m^{-3}) during the period January 2–12, 2021 detected by SENTINEL2-A and B data. The rectangular outline shown in red defines the area of analysis.

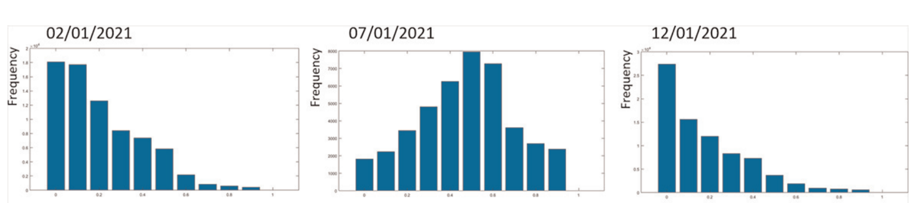

Figure 8.
Histograms for CHLA concentrations (mg.m^{-3}) during the period January 2–12, 2021 detected by SENTINEL2-A and B data.

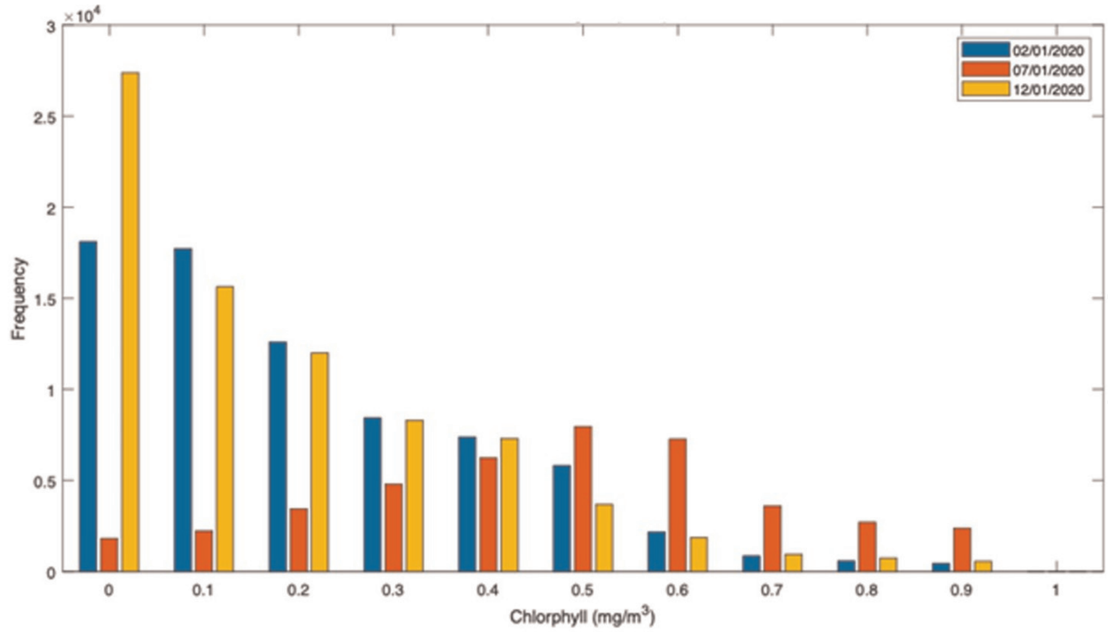

Figure 9.
Combined histogram of CHLA concentrations (mg.m^{-3}) for January 02–12, 2021 detected by SENTINEL2-A and B data.

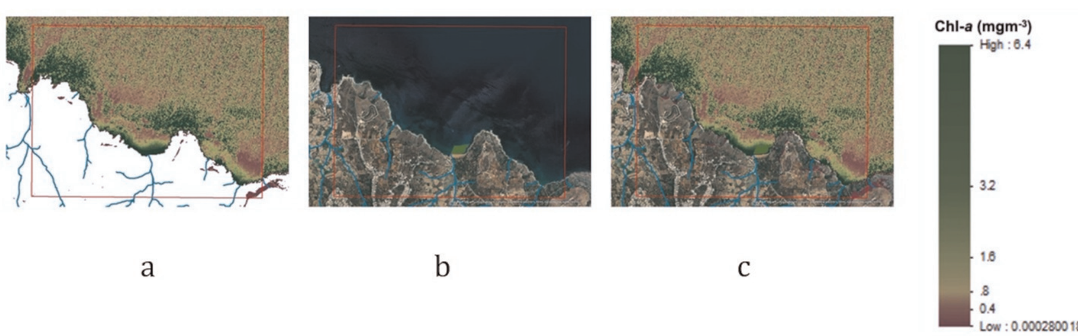

Figure 10.
SENTINEL2-A & B derived CHLA concentration (mg.m^{-3}) on January 07, 2021 (a); CHLA January climatology derived from MERIS data [14] (b); merged CHLA levels for the period January 02–12, 2021 (c). The rectangular outline shown in red defines the area of analysis.

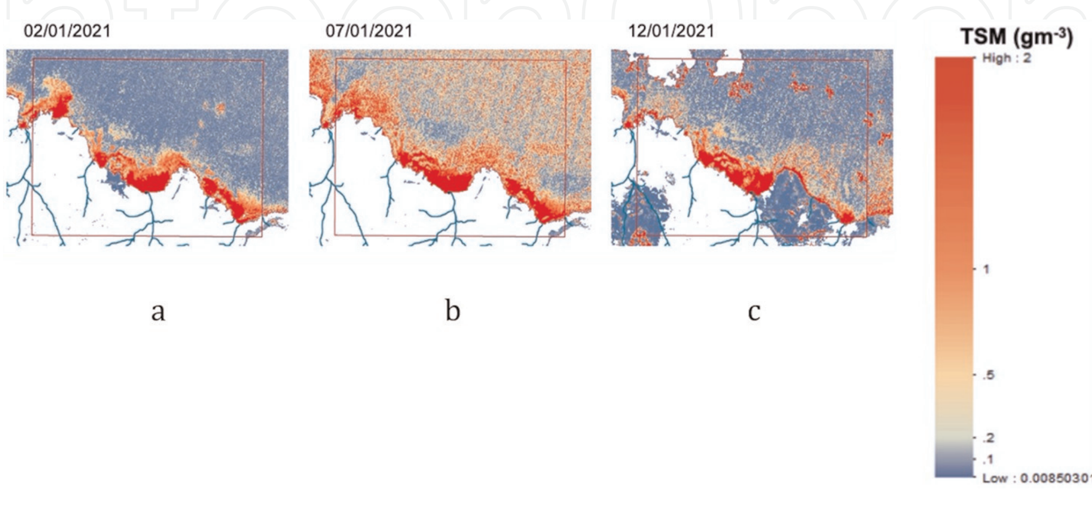

Figure 11.
SENTINEL2-A & B derived TSM concentration (g.m^{-3}) on 07/01/2021 (a); TSM January climatology (b); and merged TSM levels for the period January 02–12, 2021 (c).

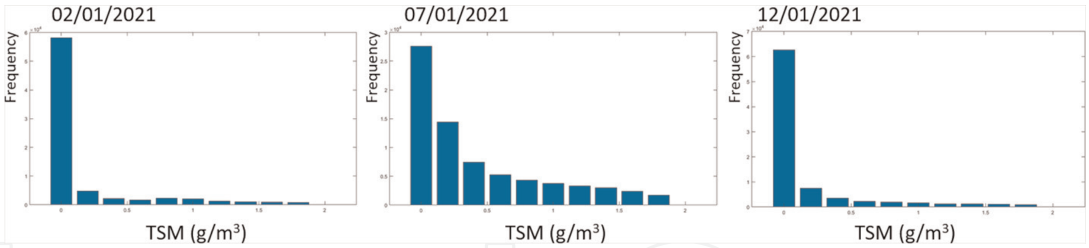

Figure 12.
Histograms showing TSM (g.m^{-3}).

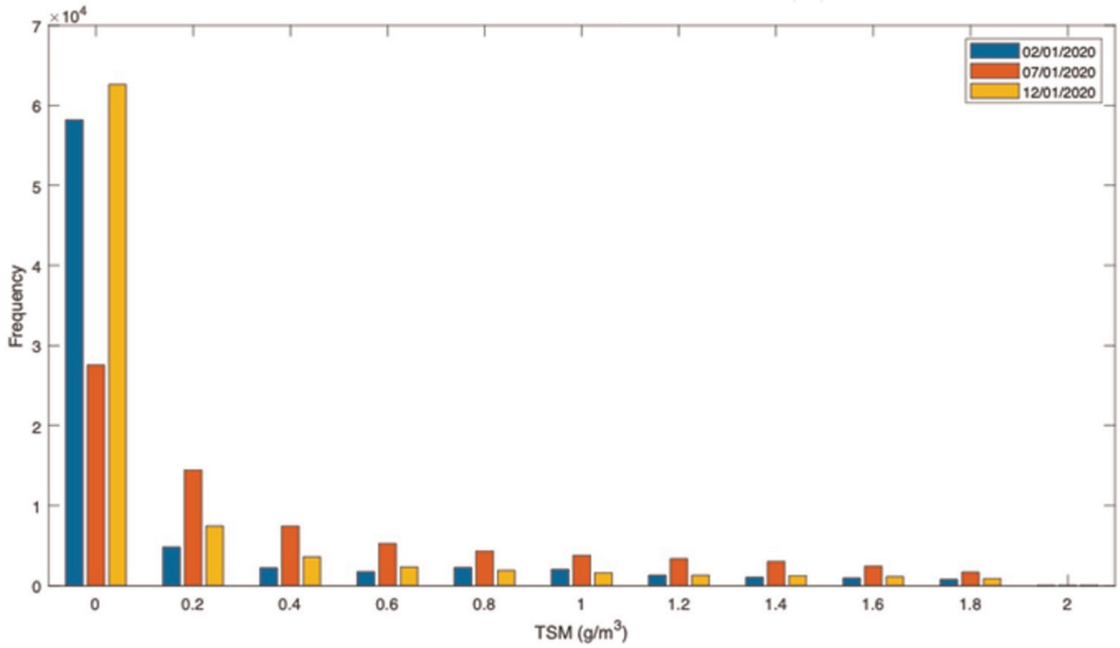

Figure 13.
Combined histogram of TSM (g.m^{-3}).

4. Discussion

This study presents a practical and multidisciplinary approach that is essential for risk management of watersheds because it helps identify the areas and factors that are most vulnerable to erosion and coastal sedimentation. Similar problems remain practically unexplored in Malta.

Soil erosion is a significant environmental issue for Malta and is having serious consequences for the sustainability of local watersheds and the agriculture sector that depends on them. Among other things, it leads to increased sedimentation along the drainage pattern identified by this study, and ultimately to increased risks of flooding and landslides within the watershed basin itself. In addition, unless properly managed, changes in the watershed dynamics will negatively affect the sensitive ecosystem dynamics observed at the Ramla valley mouth that are critical to its normal functioning.

From a risk management plan of this highly sensitive ecological watershed, it is being recommended that the impact of soil erosion hotspots identified by this study (both within the watershed itself and resulting impact on coastal waters next to the

Date	Rainstorm event		Climatological levels for January	
	TSM ($g.m^{-3}$)	CHLA ($mg.g^{-3}$)	TSM ($g.m^{-3}$)	CHLA ($mg.g^{-3}$)
January 2, 2021	0.163	0.069	0.160	0.105
January 7, 2021	0.244	0.125	—	—
January 12, 2021	0.212	0.052	—	—

Table 4.
Comparative extent between the rainstorm events and the respective climatological levels for the Ramla coastal waters next to the valley mouth.

valley mouth), are to be further monitored, and if possible, analyzed, and mitigated. Sustainable management of watersheds necessitates the use of appropriate hydrological, ecological, and socioeconomic management tools that unfortunately tend to operate, if at all, in mutual isolation. Such a thorough and holistic approach would support the much-needed management of local watersheds, which is particularly concerning and urgent in view of the need for Malta to adhere to a number of important European directives, such as the Water Framework and the Marine Strategy Framework Directive.

Future studies related to coastal water sedimentation can consider using other Earth observations platforms, such as OLCI and LANDSAT 9, to analyze more rainstorms of varying severities. Ideally, such studies would include improved algorithms to detect CHLA and TSM in coastal waters associated with watersheds. Such an integrated monitoring approach, involving both *in situ* and remote sensing analysis must also be able to give value to the validation of the entire soil erosion and sedimentation process at a highly localized scale.

It is hoped that the analysis and quantification of this phenomenon will contribute to an understanding of the dynamics of an important watershed that so far has never been studied from a soil erosion risk management point of view. The results could be used in future multi- and inter-disciplinary studies to better understand the impact of unsustainable land use practices both within watersheds and related littoral sediment budgets and to manage and develop future risk management plans aimed at minimizing soil erosion under a changing climate over the Maltese islands where evapotranspiration, rainfall, and temperatures regimes will change significantly over the next 50 years [19].

The study has a number of methodological and logistical limitations that stem from its multidisciplinary nature. In the case of the estimation of the degree of soil erosion, scientific literature on this topic is filled with the application of RUSLE for relatively large areas and therefore, the present estimates should be interpreted with care. The biggest challenge, however, concerns the *in situ* validation of the degree of soil erosion mapping estimations as identified by the 3D GIS visualization. Unfortunately, no data on actual soil losses exist at the local scale against which the present estimates can be compared.

The sedimentation processes identified in the coastal waters just outside the valley mouth can be affected by inaccuracies due to differences in resolutions used between the near-real-time Sentinel-2 datasets (having a ground resolution of 10 m) against the MERIS imagery (with a ground resolution of 300 m) used to derive climatological baselines. The use of Sentinel data at the finest resolution constituted the best freely-available data available that can be used for our soil erosion and sedimentation study at the Ramla valley mouth.

The processing of Earth observation data also had its own limitations. Firstly, restricted satellite visiting times have led to limited availability of data over the Ramla watershed, especially when studying limited, high-intensity, low-duration rainfall events. A further limitation on the methodology was posed by the presence of clouds in the satellite scenes, which tend to contaminate the sensor information acquired over any area of interest. Naturally, clouds are present during rainfall and so optical remote sensing of coastal waters can be quite challenging during, and exactly following rainstorms.

5. Conclusion

Studying soil erosion is essential for appropriate risk management of small watersheds because it helps us to identify the areas and factors that are most prone to erosion. This study describes the identification of precise locations of soil erosion hotspots that fall within the high soil erosion category (30 ton ha^{-1} $yr.^{-1}$) within the small Ramla watershed. The impact of such an intolerable degree of soil erosion in this area is being demonstrated by following the resultant deterioration of coastal water quality at the mouth of the watershed during high rainfall episodes. Based on a case study, the impact of sedimentation resulted in a 120% and 133% increase in CHLA and TSM levels respectively against background levels. The observed CHLA levels during and after rainstorms indicate eutrophic water type resulting from this sedimentation. This study provides for the first time an understanding of the causes and effects of localized soil erosion processes on the basis of which authorities should take the necessary steps to prevent its negative impacts on this watershed and interconnected coastal dynamics. In this regard, a number of recommended risk management strategies are being recommended for national authorities. These include the need to support effective soil conservation practices, strengthening of erosion control measures, and regular monitoring of coastal water quality for quality assurance purposes. Nowadays, novel remote sensing technologies, such as UAV-borne LiDAR and multispectral imaging of this watershed, are able to identify and quantify extremely high-resolution dynamics that can assist further risk management processes by providing a more accurate erodibility estimates and coastal water quality characterization at centimeter scale pixel resolution.

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Author details

Galdies Charles[1]*, Zammit Amy[1] and Gauci Adam[2]

1 Institute of Earth Systems, University of Malta, Msida, Malta

2 Faculty of Science, University of Malta, Msida, Malta

*Address all correspondence to: charles.galdies@um.edu.mt

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