Historical Hazard Assessment of Climate and Land Use-Land Cover Effects on Soil Erosion Using Remote Sensing: Case Study of Oman

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Environmental Settings

Study-Area Description

Oman, officially known as the Sultanate of Oman, is located on the southern coast of the Arabian Peninsula. This country is arid most of the year, but in monsoon seasons experiences severe rainfalls near southwestern and northeastern regions. Oman receives little rain, with an annual rainfall of 100 mm in Muscat, occurring mostly in January. In southern areas, the Dhofar Mountains have a tropical-like climate where seasonal rain from June to September resulting from the Indian Ocean's monsoon winds that provide 400 mm rainfalls. Vegetations are sparse in the interior plateau, and desert shrub and desert grass are the most common plants in Oman. The monsoon rainfall in Dhofar and the mountains area led to more vegetation growth in summer and vegetation cover is common in these regions. While the interior lands are a vast gravel desert plain with a hot and dry climate, coastal areas are humid. Oman is prone to severe soil erosion as a result

of monsoon rainfalls, especially in mountain regions. The northern and southern mountainous regions have steep slopes that experience severe rains in summer. Although soil erosion would be more apparent in coastal areas, the interior desert lands should have no significant soil erosion hazards because these regions are flat.

Precipitation Patterns

Rainfall over Oman is quite variable and irregular, depends on geographical latitudes, as shown in Fig. S1. The average yearly rainfall across Oman is 53 mm between 1979 and 2013. As it is shown, most of the year, precipitation is lower than 56 mm. However, a few anomalies happened in specific years, such as 1982 and 1996. For example, in 1982, in one hour, over 700 mm precipitation occurred in interior plateaus. Hence, although Oman has an arid and semi-arid climate in some parts, the rainfall volumes are extremely devastating in some points. These anomalies have long periods to be repeated, but they can be very serious, especially in coastal and mountain regions where the slope is steep enough to erode soils. The rainfall pattern in Oman is very distributed over central regions (Fig. S1). Salalah and northern mountains have the highest rate of rainfall, which is also in top elevations in some months covered by snow. The Salalah experiences monsoon rainfalls that originated in the Indian ocean, and in summer usually have rain in Dhofar. Rainy days (with more than 1 mm precipitation) are almost 12.4 days for Oman. These rainy days vary by location. For instance, while northern Oman mountains have only 13 days, Salalah with 34 days and Dhofar mountains with 46 days have the highest rainy days. There are high correlations between the annual rainfall and rainy days, indicating the high rainy days result in high annual rainfall. However, the rainfall and rainy days in Salalah plain and Dhofar mountains are different from other regions of Oman. These areas have a tropical-like climate and mostly experience extreme rainfalls in July and August. Rainfall intensity is the total yearly rainfall

divided by rainy days. Suppose rainfall intensity is categorized into light (R<10 mm), moderate (10<R<25 mm), heavy (25<R<50 mm), and extreme rainfall (R>50), most of the northern and southern mountains, and coastal regions have high rainfall intensity. Interior plains with lower frequencies but extreme rainfall values have extreme intensity. Also, the precipitation climate dataset is compared with observational stations in Oman, listed in Table S1. As we can see, the comparisons have good accuracy to detect rainfall patterns, although some uncertainties are inevitable.

Land-use Patterns

Oman is an arid and semi-arid region that is covered by bare lands. 0.1 % of the country is covered by pastures and meadows, 5.9% by sparse vegetation, 1% by croplands, and 92.5% by bare lands. The forests are mainly distributed in the Salalah plains and Dhofar mountains. However, other regions are covered by deserts, even in the coastal areas. Drought and limited rainfall may pose some challenges to the water supply. However, 94% of available water resources are used for agriculture and 2% for industrial activities, with the main source in fossil soil in desert lands and spring water in hills and mountains.

The land cover variation is not homogeneously distributed. Regardless of the desert lands, the irrigated croplands are concentrated in some limited areas, e.g., Salalah, which produces Fruits and Vegetables, Al Kamil that produces Dates, Nizwa cultivates Wheat, Suhar that grows Dates, Muscat, and Khasab that make Citrus, Dates, and Fruits. The rangelands of Oman occupy nearly 41 (million ha) and are considered an important environmental asset and a source of the nation's biodiversity and forage reserves. They provide around 4% of the animal feed needed for red meat livestock in Northern Oman and as high as 63 percent of the feed requirements in Dhofar in the south.

Data from 1961 to 2012 on land use and agriculture in the Sultanate of Oman indicates that: the contribution of agriculture to GDP has been 46% in the 1960s, decreased to 2% in 2012; and now provides only about 5% of the total employment; the rural population decreased from 76% of the total population in 1960s to 28% in 2012; agricultural productivity indexes (crop production, food production, livestock production, and cereal yield) have substantially increased over time and technology adoption in agriculture (use of machinery and fertilizer) has increased.

Soil Properties

Most of the land in Oman is desert lands, arid/semi-arid plains, and mountains, with the pronounced scarcity of water and non-productive soil. Soil surveys have revealed that only about 7.18% of the total country area (about 2.223 million ha out of the 30.95 million ha) is suitable for agricultural activities, of which 0.79 (million ha) are highly suitable and 1.43 (million ha) are moderately suitable.

The soil parent materials in Oman are alluvium generated by sediment processes in the last glacial ages. Therefore, Oman soil surfaces already have a high potential for erosion. However, soil erodibility in surfaces may be affected by weathering, tangential wind stresses, and anthropogenic factors. Soil erosion in Salalah is mainly because of anthropogenic activities, which have high soil erosion potential, especially in higher elevations.

Elevation Properties

The mountains in Oman are majorly elevated in northern regions from Al-Hasid to Khasab and southern regions near Salalah's shores. The highest elevation is Jabal Shams, with 2980 meters above sea level north of Al-Hamra town. The Hajar mountains are the place of the Gulf's wildest

habitats with soaring birds of prey surfing on high-altitude thermals, acacias sprouting small, perfumed flowers in the rocky hillside, and huge, dramatic drops that will send your heart racing.

The northern part of the Oman mountains includes the largest extent, best exposures, and the complete sections through the ca 15–20 km thick Semail ophiolite. To these extents, various Jebels such as Sumeini and Ghawil are mostly used for the mining of copper and are covered by a flat plain under the mountains with a volcanic source and a folded sediment on the surface. For example, in Sumeini Window, erosion has exposed a complete section through the base. Therefore, these regions are prone to soil erosion, especially where steep slopes provoke the situation.

The southern province of Oman, Dhofar, is bounded by the Indian Ocean along the south, the Yemen border in the west, and the great sand sea of the Rub al-Khali or Empty Quarter to the north. The coastal region of Dhofar is dominated by strike-slip faults along the Arabian plate margin. These mountains are covered by prairie vegetation and in some parts with sparse forests. These regions have steep slope enchants triggered by monsoon rainfalls and should experience extreme sheet and rill erosion.

The elevation description of Oman can be divided into three major classes.

1. **The coastal plain**. The most important parts are the Batinah Plain in the north, which is the principal agricultural area, and the Salalah Plain in the south. The elevation ranges from 0 near the sea to 500 meters further inland.
2. **The mountain ranges,** which occupy 15 % of the total area of Oman. The mountain range runs from Musandam in the north to the Ras Al-Hadd in the southeast. In the north, close to the Batinah Plain, is the Jebel Al Akhdar with a peak of 3000 meters. Other mountains are located in the Dhofar province, in the extreme southern part of the country, with peaks from 1000 to 2500 meters.

3. **The internal regions**. Between the coastal plain and the mountains in the north and south lie the internal regions, with elevations not exceeding 500 meters. This part covers 82 % of the country with mainly desert, sand, and gravel plains. It includes part of the Rub' al Khali, also known as the Empty Quarter or the Great Sandy Desert.

These areas have specific elevation profiles that form landscapes. The Landform datasets also represent these differences with elevation classes (Fig. S2). As we can see, Salalah in Dhofar mountains and Jebel Shams in the north are High Mountains and in lower elevation classified as Low Mountains. However, some of these mountains are scattered near the offshores of Khasab and Sawqirah. The interior lands are Flat or Nearly Flat Plains except near Rub Al-Khali desert with Scattered Hills, High Hills and to some extent near Dhofar of Tablelands with Very High Relief. Therefore, most of the interior plateaus are desert land with smooth and flat plains that are rarely covered by some local reliefs.

Digital Elevation Models (DEM) also represent these classes in terms of absolute numbers (Fig. S3). As we can see, the elevation profile represents the highest mountains are scattered in northern and in Dhofar regions. However, southern regions have higher averages of elevations covered by Low and High mountains and moderate hills. The coastal regions have the lowest expected elevations except in Sur that the high elevation ridge is continued along offshore coastal regions. Therefore, the mountains and hills should have a higher susceptibility for steepest slopes, while the northern areas also have the highest slope length.

Table S1 Comparison between observation stations and IMERG dataset

Station	POD	CSI	MAE	RMSE	RBIAS	CC
Adam	0.70	0.06	0.02	0.44	0.00	0.27
Bahla	0.71	0.06	0.03	0.47	0.00	0.26
Diba	0.64	0.06	0.03	0.33	0.00	0.32
Fahud	0.54	0.07	0.01	0.34	0.00	0.22
Haima	0.22	0.03	0.01	0.29	0.02	0.23
Ibra	0.66	0.10	0.03	0.61	0.00	0.32
Ibri	0.65	0.09	0.02	0.42	0.00	0.17
Jabal Shams	0.64	0.07	0.05	0.64	0.00	0.17
Joba	0.61	0.07	0.01	0.36	0.00	0.38
Khasab Port	0.67	0.08	0.04	0.53	0.00	0.16
Madha	0.63	0.11	0.03	0.46	0.01	0.07
Majis	0.67	0.10	0.02	0.34	0.00	0.30
Masirah	0.62	0.03	0.03	0.87	0.01	0.51
Nizwa	0.69	0.08	0.03	0.46	0.00	0.12
Qalhat	0.15	0.04	0.07	0.51	0.00	0.43
Rustaq	0.62	0.07	0.03	0.47	0.00	0.29
Saham	0.64	0.18	0.03	0.43	0.01	0.42
Saiq	0.71	0.07	0.05	0.51	0.00	0.27
Salalah	0.11	0.07	0.02	0.69	0.00	0.42
Samail	0.76	0.09	0.03	0.43	0.00	0.39
Sunaynah	0.68	0.09	0.02	0.51	0.00	0.18
Sur	0.68	0.09	0.03	0.43	0.00	0.36
Suwaiq	0.65	0.11	0.03	0.45	0.00	0.22
Thumrait	0.69	0.04	0.01	0.25	0.01	0.26
Yalooni	0.18	0.03	0.01	0.24	0.00	0.00
Yanqul	0.77	0.12	0.04	0.65	0.01	0.26
Total	0.59	0.08	0.03	0.47	0.00	0.27

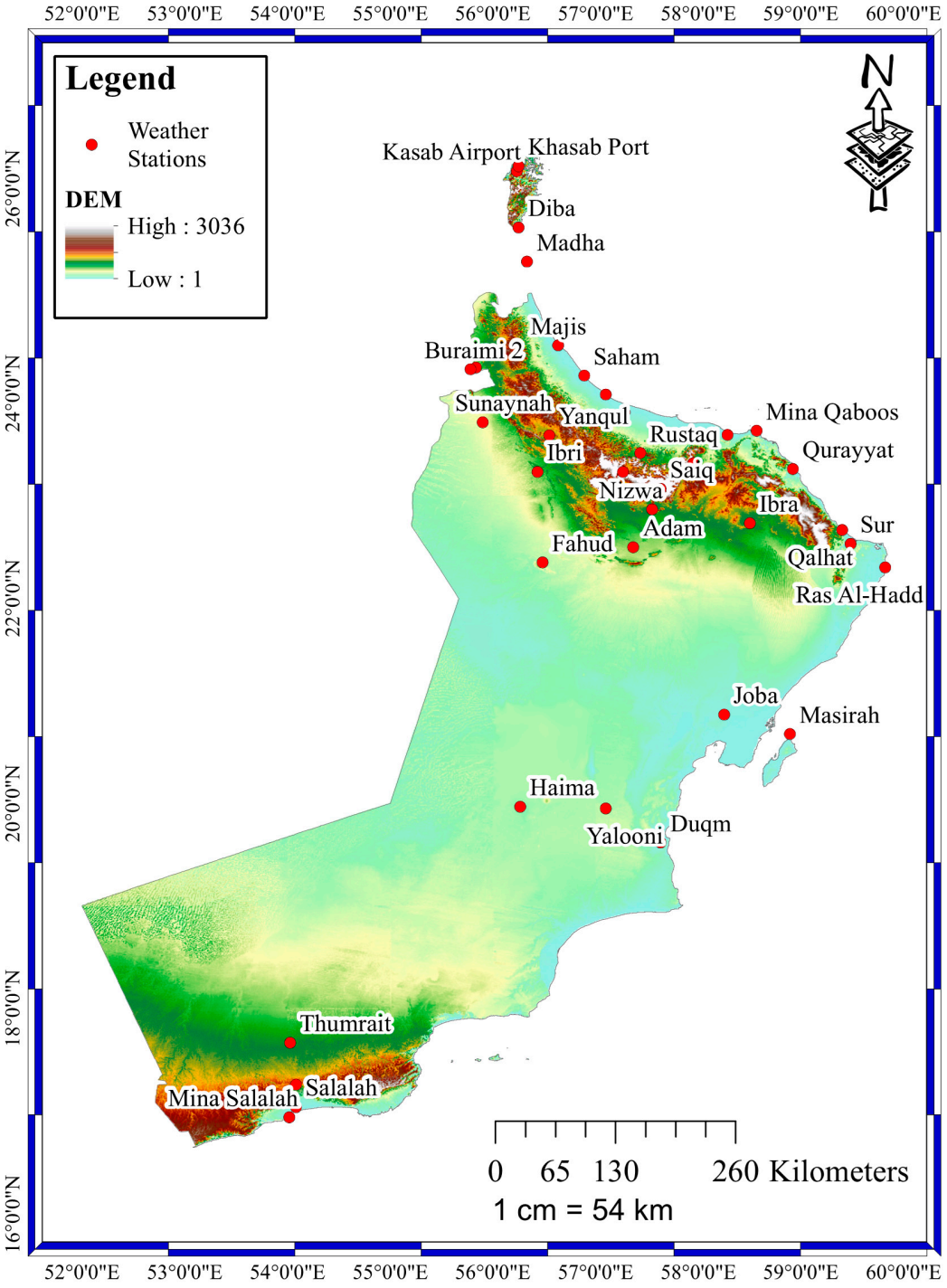


Figure S1. Meteorological Stations across Oman.

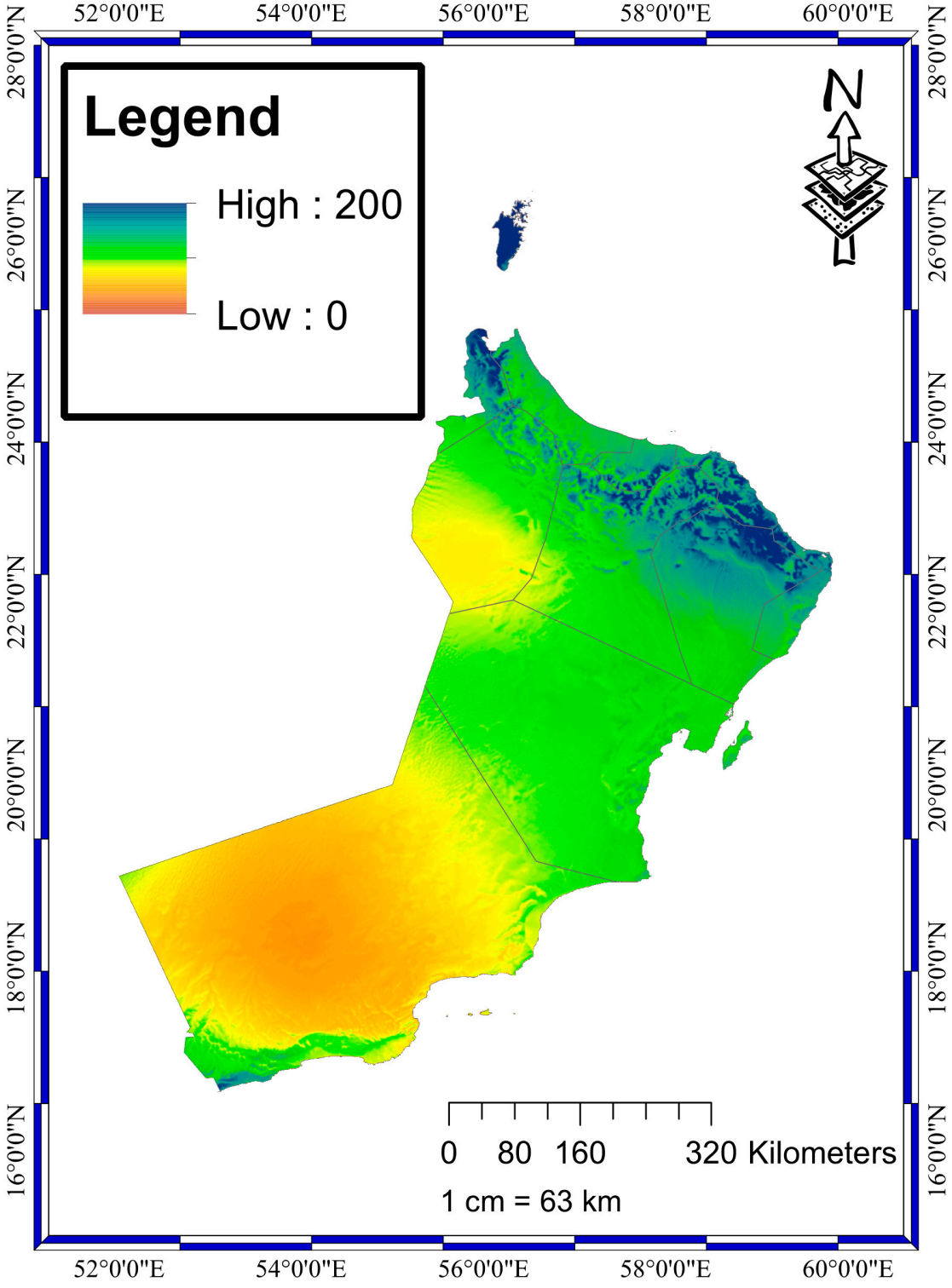


Figure S2. Average Precipitation (mm) map of Oman.

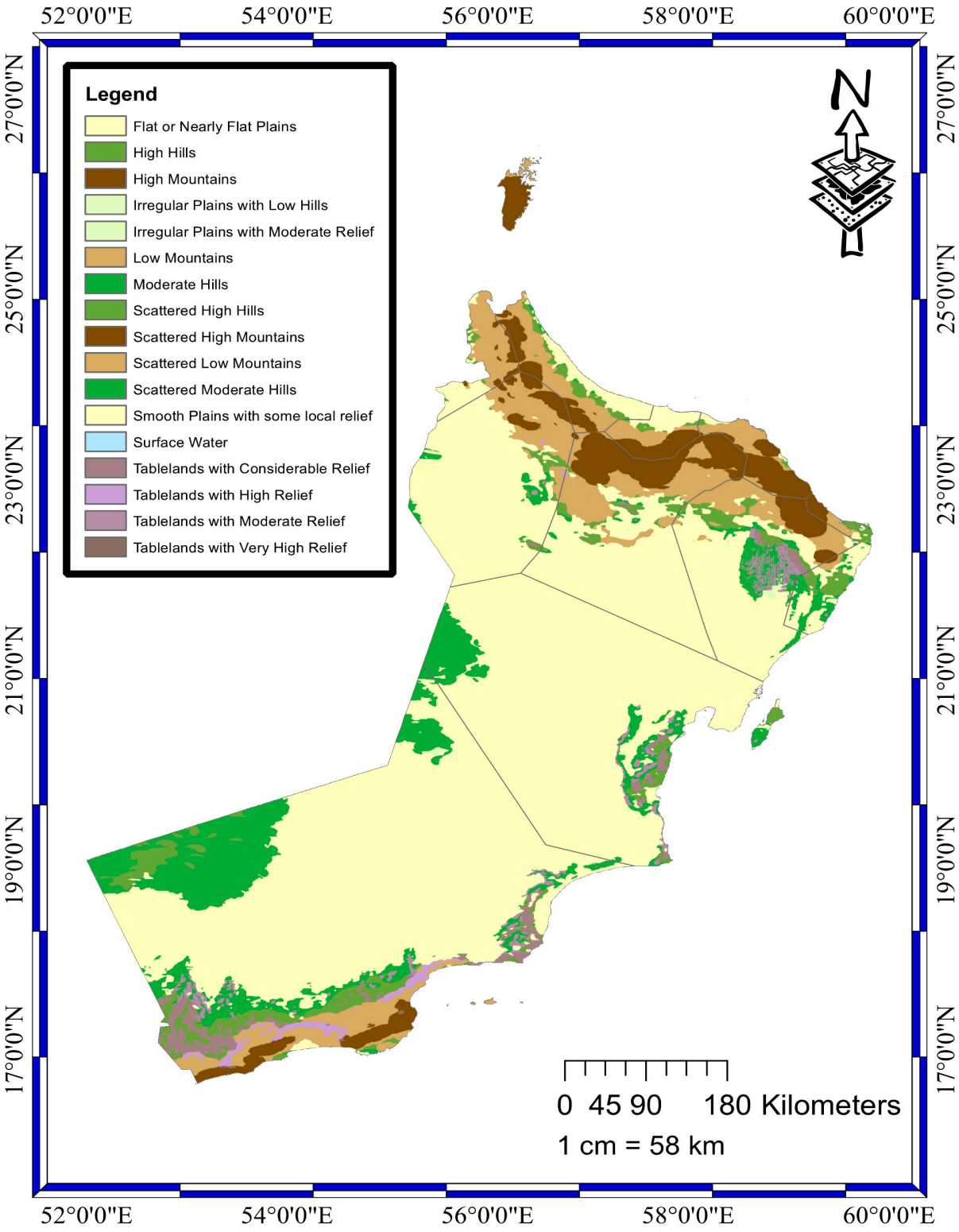


Figure S3. Oman landform based on land profiles.

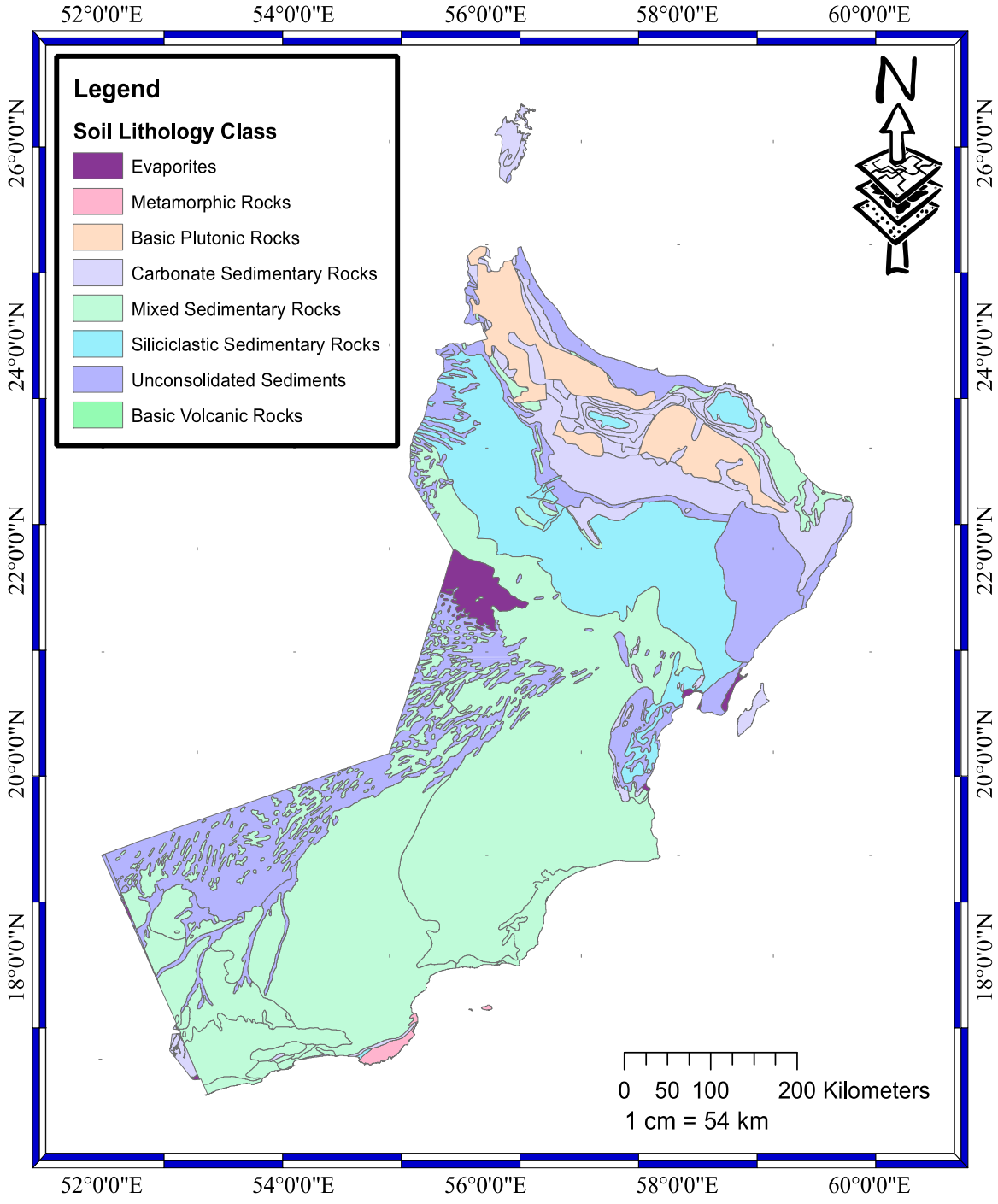


Figure S4. Soil lithology map of Oman.