RUSLE parameter calculations for Magna Roman Fort.

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This document contains supplementary material for the paper: 'Integration and analysis of multi-modal geospatial secondary data to inform management of at-risk archaeological sites'. In particular it details the methodology used to calculate parameters in the RUSLE model and briefly reports on some results that were not included within the main paper.

Methodology

Topographic Factor (LS)

The LS factor is one of the input parameters into the Revised Universal Soil Loss Equation (RUSLE) used to study soil erosion risk at Magna. It summarises the effects of topography on soil erosion, combining the influence of both slope length (L) and slope steepness (S). To calculate the LS factor, we have used equations proposed by [1]'s algorithm, given by,

$$LS = L \times S \tag{1}$$

$$L = \left(\frac{\lambda}{22.13}\right)^m \tag{2}$$

$$m = \frac{\beta}{1 + \beta} \tag{3}$$

$$\beta = \frac{\sin(\vartheta)}{3(\sin(\vartheta)^{0.8}) + 0.56} \tag{4}$$

$$S = \begin{cases} 10.8\sin(\vartheta) + 0.03, & \vartheta < 9\% \\ 16.8\sin(\vartheta) - 0.5, & \vartheta \geq 9\% \end{cases} \tag{5}$$

where λ is the slope length (in meters), m is the variable length-slope exponent ranging from 0 to 1, β is the ratio of the rill to interill erosion and ϑ is the slope angle. [2] and [3] suggested slope length should be limited to a maximum threshold of 333m as the reliability of RUSLE at these long slope lengths is questionable. Furthermore, empirical evidence and thus validity suggest that RUSLE should be limited to slope gradients less than 50% [4].

A LiDAR Digital terrain model (DTM) with a spatial resolution of 1m produced by the Environment Agency, was used for the LS factor computation [5]. The hydrology toolset on ArcGIS Pro, available with the Spatial Analysst license, was employed for data processing and computation [6]. For data pre-processing, the fill sink algorithm was used to create a depressionless DEM. Flow accumulation and slope were derived and limited according to the thresholds described above, and equations (1) - (5) were applied using the raster calculator tool to compute an LS factor map of Magna and the surrounding land. The main limitation of this methodology is the presence of landscape features e.g. roads, stone walls or fences that may interrupt runoff and reduce the slope length but are not identified in the DTM [7]. Further processing could identify and map these features, but for simplicity this has not been carried out in this study.

Rainfall Erosivity Factor (R)

Rainfall is the main driver of soil erosion by water and rainfall erosivity (R) quantifies the relationship between rainfall and sediment yield [8]. Rainfall erosivity of a storm event is calculated directly from high temporal resolution precipitation data by multiplying the total kinetic energy of the storm event by the maximum 30-minute intensity. The R factor then accumulates these values over all rainfall events and averages it over multiple years [9,10]:

$$R = \frac{1}{n}\sum_{j=1}^{n}\sum_{k=1}^{m_j}(EI_{30})_k \quad (6)$$

where R is the average annual rainfall erosivity (MJ mm ha^{-1} h^{-1} yr^{-1}), n is the number of years of data, m_j is the number of erosive events in year j, and EI_{30} is the rainfall erosivity index of a storm event k. The event erosivity EI_{30} (MJ mm ha^{-1} h^{-1}) is defined as:

$$EI_{30} = \left(\sum_{r=1}^{m} e_r v_r\right) I_{30} \quad (7)$$

where e_r is the unit rainfall energy (MJ ha^{-1} mm^{-1}),v_r is the rainfall volume (mm) during the time period r, and I_{30} is the maximum rainfall intensity during a 30 minute period of the storm event (mm h^{-1}). The unit rainfall energy, e_r is calculated for each time interval, r as follows:

$$e_r = 0.29[1 - 0.72\exp(-0.05 i_r)] \quad (8)$$

where i_r is the rainfall intensity during the time interval (mm h^{-1}). The criteria proposed to define the delineation of an individual storm event is a cumulative rainfall volume of less than 1.27mm falling in six hours [11]. [12] suggested that at least 15 years of data are required to obtain representative estimates of annual erosivity. Thus, the lack of availability of high temporal resolution precipitation data, for sufficient periods of time, have limited the calculation of rainfall erosivity in many soil erosion studies [13].

The ESDAC developed a Rainfall Erosivity Database at European Scale (REDES) based on calculations using high temporal resolution data (5 to 60 minutes) for rainfall stations across Europe [14]. However, under closer inspection only 39 stations were included for the UK, over half of which had less than 15 years of data. More importantly, available precipitation records were found for UK stations nearby Magna that were not included in the study. Therefore, to obtain a more accurate estimation of the rainfall erosivity at Magna, its seasonal variation, and future projections, we first created maps of the R factor and monthly erosivities over the UK. This included the following steps: (a) The collection and compiling of hourly precipitation data from stations across the UK for the years 1995-2019, (b) the calculation of the R-factor and monthly erosivities for each precipitation station, and (c) the spatial interpolation of R-factor point values.

Hourly precipitation records were obtained from the Met Office Integrated Data Archive System (MIDAS) [15]. Stations were selected based on the following criteria: (1) at least 15 years of precipitation data were available between the years 1995 - 2019, (2) years were included if they contained less than 10% missing hourly records. This resulted in the selection of 123 precipitations stations with an average of 22.9 years of high temporal resolution precipitation data. Figure 1 shows the station locations. R factors were then calculated for each station based on equations (6) - (8) using the 'hyetor' R package [16]. For each month, average monthly erosivity was also calculated by modifying equation (6) to accumulate EI_{30} over individual months rather than years. The resulting rainfall erosivity database can be found in the project's GitHub repository (accessed via: https://github.com/Adam-Booth/Group3_Project)

A spatial regression approach, specifically a generalised linear mixed model with an additive spatial component, was used to interpolate point values and infer the distribution of rainfall erosivity in the UK from a series of correlated, but independent, climate covariates. Specifically, covariates included average monthly precipitation, average minimum and maximum monthly temperature, bioclimatic variables, elevation, latitude and longitude.

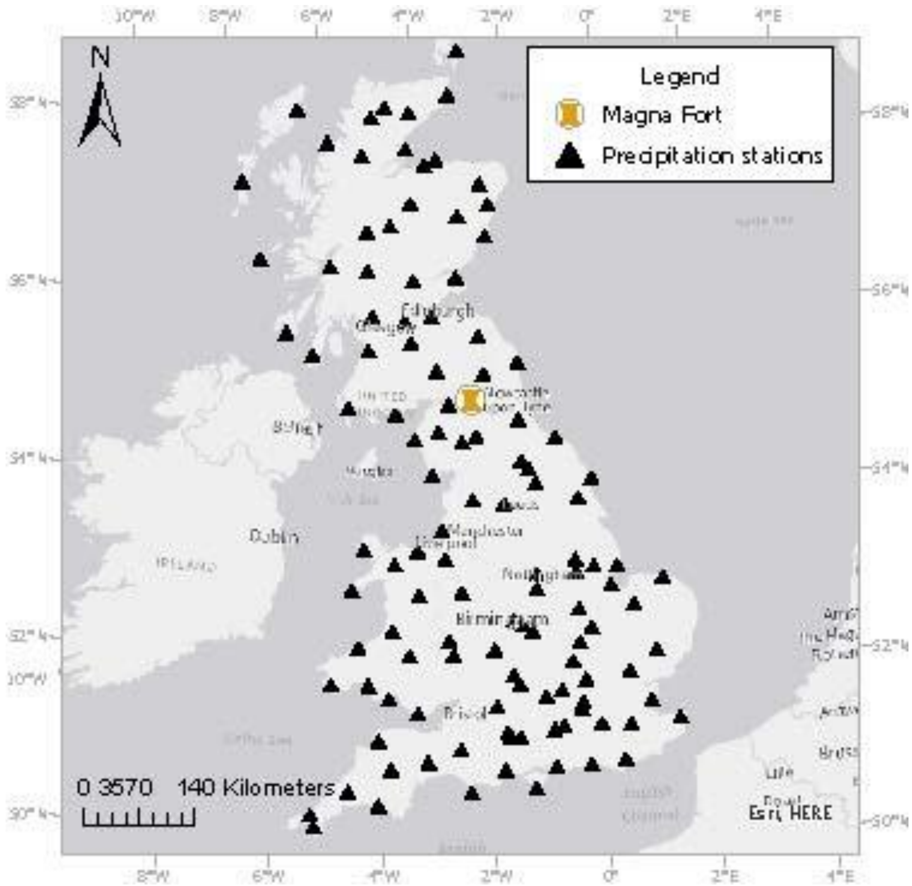

Figure 1: Map showing the location of UK rainfall stations used to calculate R factors.

Climatic variables were derived for the period 2000-2018 from the WorldClim database [17], which reports monthly averages of precipitation and temperature globally at 1-km resolution. 13 regression models were fitted for each individual monthly R factors and the yearly R factor. For each model specific covariates to be included were selected based on correlation coefficients with the dependent variable. Model performance was evaluated using the coefficient of determination (R^2), root mean square error (*RMSE*), and mean average error (*MAE*) based on a 10-fold cross validation.

Using the fitted regression models, future rainfall erosivity was estimated for the periods 2021-2040, 2041-2060, 2061-2080 and 2081-2100, under different future climate scenarios, or Representative Concentration Pathways (RCPs). Climate covariates for future projections were obtained from the WorldClim database [17], using the CNRM-CM6-1 climate model developed by the CNRM-CERFACS group for CMIP6 [18]. This global climate model (GCM) was selected as it was one of the only European GCMs available as downscaled 1km data comparable to the WorldClim baseline data used to train the regression models. Climate projections are model-driven descriptions of potential future climates under a given set of possible climate change scenarios, and thus, GCMs represent powerful tools to produce spatially explicit predictions on future climate scenarios [19]. However, given that rainfall intensity and duration have large uncertainty in future predictions, results should be interpreted with caution. Among the 3 climate scenarios we have selected for this study; RCP2.6 is the conservative pathway, RCP 4.5 is the intermediate scenario and the most widely used, and RCP8.5 represents a business-as-usual scenario and the most extreme changes to climate. For each period and climate scenario, monthly erosivity and R factor were estimated for the UK and then averaged over the site of Magna to extract a time series of projected future values.

Other Parameters

EU-wide maps of the C, K and P factors, obtained from the ESDAC [20], were cropped to the same extent as the NY66NE UK DTM tile obtained from the Environment Agency [5] and used as the corresponding input layers into the RUSLE model.

Results

The mean value for soil erodibility (K) over the field at Magna is 0.0275. The mean value for the cover management factor (C) is 0.0793. This value ranges from 0.001 to 0.113 in the larger area covered by the tile, which we regard as a suitably accurate approximation based on values suggested in literature for low productivity grassland [21]. The P factor was estimated to be 1 across the area of Magna Fort, reflecting that no conservation practices are currently in place to limit erosion. This contradicts the existence of stone walls on the site, which should reduce the value. Further processing by mapping the stone walls using aerial photography and DTMs could be done to improve its accuracy [22]. However, given the relatively small area that the stone walls cover, disruptions to erosion estimates will be minimal and instead these features should be considered when interpreting the RUSLE results. For this study, the C, K and P factors are considered as sitewide constants due to the relatively small area covered by Magna and the lack of identifiable variation in sediment or vegetation cover across the site.

The value for LS ranged from 0 to 42.62 in the area encompassing the fort, with a mean of 1.09. Spatially, the topographic factor is the only dynamic aspect of the RUSLE. Consequently, the results of the RUSLE formula will vary as a function of slope across the site, reflecting the primacy role of slope as a factor in erosion risk across smaller areas [23].

The rainfall erosivity factor was calculated for each of the 123 stations with long-term high temporal precipitation records available. The resulting database of station wise R factors is available at the GitHub Repository. The rainfall erosivity across stations ranged from 287.67 to 3016.63 MJ mm $ha^{-1}h^{-1}y^{-1}$, with an average of 591.35 MJ mm $ha^{-1}h^{-1}y^{-1}$. Monthly values were also calculated, with April having the lowest average erosivity and August having the highest, at 22.05 and 77.58 MJ mm $ha^{-1}h^{-1}y^{-1}$ respectively. Point values were then interpolated using the spatial regression approach described in the preceding section. A summary of the cross-validation statistics are shown in Table 1. Performance of the annual model was relatively high, with an R^2 value of 0.59, while the monthly prediction models had more variation in their performance due to limitations in the number of covariates [24]. Performance of the monthly models for October to May proved to be generally high, resulting in R^2 values between 0.44 and 0.62. However, summer months' R factor were less well predicted in terms of R^2, particularly July with R^2 values of 0.11. However, it was noted that summer months tend to have a broader range and higher variability of R-factor values, which could partly account for this higher error. Moreover, under closer inspection of the points wrongly predicted by our models, larger errors were introduced when predicting high values of rainfall erosivity. These values are likely due to extreme storm events whose distribution cannot be captured by a model based on averaged covariates. Given that stations close to Magna rarely observed events of these magnitudes, results can be trusted for our purpose.

Table 1: Cross validations statistics for models used to interpolate rainfall erosivity over the UK.

model	R2	rmse	mae
R	0.5878094	246.219489	124.865667
jan	0.5447863	50.675697	18.924045
feb	0.6215346	34.564569	12.484177
mar	0.5398655	36.813404	11.890062
apr	0.4627176	9.873895	5.611972
may	0.4367953	11.111546	7.266645
jun	0.2399112	17.563723	12.086254
jul	0.1071338	28.328712	19.913047

model	R2	rmse	mae
aug	0.2324451	25.055743	18.637212
sep	0.3350835	27.804575	14.210824
oct	0.4745453	37.152341	19.457581
nov	0.5926360	34.047407	17.032098
dec	0.5170692	62.647806	22.561478

The fitted models were then applied to produce annual and monthly maps of the estimated R-factor. Figure 2 shows the resulting annual rainfall erosivity map of the UK. There is a clear trend of increasing erosivity from east to west, with northwest Scotland experiencing the highest rainfall erosivities, and south east England experiencing the lowest. Values of rainfall erosivity were then extracted for the site surrounding Magna. Annual rainfall erosivity at our site was estimated to be 597 MJ mm $ha^{-1}h^{-1}y^{-1}$. Further details of monthly maps of UK rainfall erosivity can be found at the GitHub repository. Details of future monthly and annual rainfall erosivity can also be found at this link and in the corresponding paper.

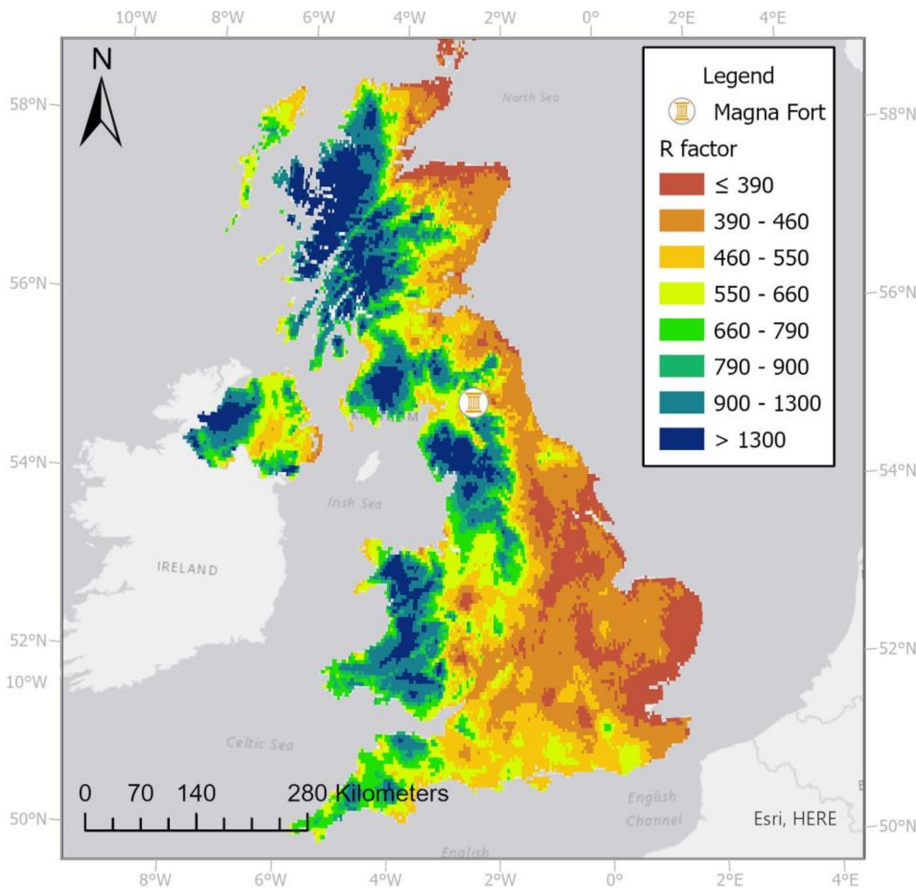

Figure 2: Map of annual rainfall erosivity in UK (MJ mm $ha^{-1}h^{-1}y^{-1}$)

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