Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-68
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 23 February 2018

Hydrology and Earth System Sciences
Open Access
Discussions

A review of the (Revised) Universal Soil Loss Equation (R/USLE): with a view to increasing its global applicability and improving soil loss estimates

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Abstract. Soil erosion is a major problem around the world because of its effects on soil productivity, nutrient loss, siltation in water bodies, and degradation of water quality. By understanding the driving forces behind soil erosion, we can more easily identify erosion-prone areas within a landscape and use land management and other strategies to effectively manage the problem. Soil erosion models have been used to assist in this task. One of the most commonly used soil erosion models is the Universal Soil Loss Equation (USLE) and its family of models: the Revised Universal Soil Loss Equation (RUSLE), the Revised Universal Soil Loss Equation version 2 (RUSLE2), and the Modified Universal Soil Loss Equation (MUSLE). This paper reviewed the different components of USLE and RUSLE etc., and analysed how different studies around the world have adapted the equations to local conditions. We compiled these studies and equations to serve as a reference for other researchers working with R/USLE and related approaches. We investigate some of the limitations of R/USLE, such as issues in data-sparse regions, its inability to account for soil loss from gully erosion or mass wasting events, and that it does not predict sediment pathways from hillslopes to water bodies. These limitations point to several future directions for R/USLE studies: incorporating soil loss from other types of soil erosion, estimating soil loss at sub-annual temporal scales, and using consistent units for future literature. These recommendations help to improve the applicability of the R/USLE in a range of geoclimatic regions with varying data availability, and at finer spatial and temporal scales for scenario analysis.

1 Introduction

Soil erosion involves many processes but one effect is particles being transported and deposited from one location to another. Although it occurs naturally, it is often exacerbated by anthropogenic activities (Adornado et al., 2009). Soil erosion is affected by wind, rainfall and associated runoff processes, vulnerability of soil to erosion, and the characteristics of land cover and management (Aksoy & Kavvas, 2005). Managing and understanding erosion and associated degradation is critical because of its possible effects: nutrient loss, river and reservoir siltation, water quality degradation, and decreases in soil productivity (Bagherzadeh, 2014). In a review of the costs of soil erosion, Pimentel et al. (1995) reported soil erosion rates for regions around the world: Asia, South America, and Africa with an average of 30 to 40 ton ha^{-1} yr^{-1} and an average of 17 ton ha^{-1} yr^{-1} for the United States of America and Europe. For comparison, the soil erosion rate for undisturbed forests was reported to range from 0.004 ton ha^{-1} yr^{-1} to 0.05 ton ha^{-1} yr^{-1} globally (Pimentel et al., 1995). Within a landscape, erosion due to water can be caused by unconcentrated flow (sheet), within small channels (rills), raindrop impact and overland flow (inter-rill), and larger channels of concentrated flow (gullies) (Aksoy & Kavvas, 2005; Morgan, 2005). Understanding how these processes occur and what areas are vulnerable to erosion are paramount to land management, and advances in technology have assisted in making this process faster and more accurate.

Soil erosion models aid land management by helping understand sediment transport and its effects on a landscape. They range from relatively simple empirical models, and conceptual models, to more complicated physics-based models (Merritt et al., 2003). Extensive reviews of soil erosion models of varying complexity have been done before, but tend to focus on input requirements and applications (Aksoy & Kavvas, 2005; Merritt et al., 2003). A review by de Vente & Posen (2005) differs by focusing on semi-quantitative models that include different types of soil erosion in order to estimate basin sediment yield. Other reviews have focused on the use of different types of soil erosion models in particular places, such as Brazilian watersheds for de Mello et al. (2016). These papers reviewed soil erosion models in terms of their complexity and input requirements (Aksoy & Kavvas, 2005; Merritt et al., 2003). This family of Universal Soil Loss Equation (USLE) models include the original USLE, the Revised Universal Soil Loss Equation (RUSLE), the Revised Universal Soil Loss Equation version 2 (RUSLE2), and the Modified Universal Soil Loss Equation (MUSLE). The main contribution of this review is a comprehensive compilation of equations for the different components of the original USLE and the updated RUSLE, analysing their data requirements, and providing guidance as to which equations are most appropriate over a range of geoclimatic regions with varying levels of data availability.

The USLE is an empirical model used to estimate the average rate of soil erosion for a given combination of crop system, management practice, soil type, rainfall pattern, and topography (Wischmeier & Smith, 1978). An updated form of USLE (RUSLE) was published to include new rainfall erosivity maps for the United States of America and improvements to the method of calculating the different USLE factors (Renard et al., 1997). RUSLE accounted for changes in soil erodibility due to freeze-thaw and soil moisture, a method for calculating cover and management factors, changes to how the influence of topography is incorporated into the model, and updated values for conservation practices (Renard & Freimund, 1994). The RUSLE2 framework is a computer interface to handle more complex field situations, including an updated database of factors (Foster et al., 2003). These three variations of R/USLE measure soil loss at an annual time scale, but the MUSLE uses runoff and peak flow rate to estimate event-based soil loss (Sadeghi et al., 2014). None of these approaches originally include seasonal soil loss, but this paper points to improvements in seasonal soil loss estimation as a future direction for R/USLE studies.

This paper focuses on previous applications of USLE, and RUSLE. The original work by Wischmeier and Smith (1978) serves as the main reference for the original USLE, the RUSLE is documented in work by Renard et al. (1997), and changes for RUSLE2 are documented in Foster et al. (2003). All of these works document the models and their application in the United States of America, but these models have been used around the world due to their relative simplicity and seemingly low data requirements (Appendix 1).

This relative simplicity of the R/USLE allows it to be integrated into other soil erosion models to help with management and decision-making. Previous reviews identified R/USLE as a component of more complex models, such as the Agricultural Non-Point Source model (AGNPS), the Chemical Runoff and Erosion from Agricultural Management Systems model (CREAMS), the Productivity, Erosion and Runoff, Functions to Evaluate Conservation Techniques model (PERFECT), and the Sediment River Network model (SedNet) (Aksoy & Kavvas, 2005; de Vente & Poesen, 2005; Merritt et al., 2003). The AGNPS estimates upland erosion using the USLE and then uses sediment transport algorithms to simulate runoff, sediment and nutrient transport within watersheds (Aksoy & Kavvas, 2005). The usage of RUSLE in large models is mainly for the purpose of assisting with decision-making, such as prioritising land use objectives in the Philippines (Bantayan & Bishop, 1998), scenario analysis for water quality in catchments in New Zealand (Rodda et al., 2001), or delineating unique soil landscapes in Australia (Yang et al., 2007). This review addresses the complexity of the different factors, and things for researchers to consider before applying R/USLE to their study area. The MUSLE is not included in this review because an extensive review of the model has already been done by Sadeghi et al. (2014) and event-scale estimates are beyond the scope of this paper.

2 Universal Soil Loss Equation (USLE)

The principal equation for the USLE model family is below:

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

Where:

A	Mean annual soil loss (metric tons hectare^{-1} year^{-1})
R	Rainfall and runoff factor or rainfall erosivity factor (megajoules millimetre hectare^{-1} hour^{-1} year^{-1})
K	Soil erodibility factor (metric tons hectare hour megajoules^{-1} hectare^{-1} millimetre^{-1})
L	Slope-length factor (unitless)
S	Slope-steepness factor (unitless)
C	Cover and management factor (unitless)
P	Support practice factor (unitless)

The USLE was originally developed for the United States of America, but has seen use in many other countries since then. Work by Panagos et al. (2015e) has applied a form of RUSLE to the geographic area of the European Union. The appendix of this paper compiles a non-exhaustive list of studies that have applied the USLE and RUSLE models to watersheds around the world. The uncertainties from soil erosion modelling also stem from the availability of long-term reliable data for modelling, which is a problem not unique to R/USLE applications and is more pressing for more complex models that have high data inputs (de Vente & Poesen, 2005; Hernandez et al., 2012). Hence, the ubiquitous usage of the R/USLE can be attributed to its relatively lower data requirements compared to more complex soil loss models, making it potentially easier to apply in areas with scarce data.

Although the application of the R/USLE seem to be a simple linear equation at first glance, this review addresses the complex equations that go into calculating its factors, such as rainfall erosivity which requires detailed pluviographic data (< 30 minute resolution). This paper discusses the advantages, disadvantages, and limitations of the USLE model family. Although alternative equations are presented, we also discuss questions of suitability that future users should consider before applying the R/USLE.

2.1 Rainfall erosivity factor (R)

The R-factor represents the effect that rainfall has on soil erosion and was included after observing sediment deposits after an intense storm (Wischmeier & Smith, 1978). The annual R-factor is a function of the mean annual EI_{30} that is calculated from detailed and long-term records of storm kinetic energy (E) and maximum thirty-minute intensity (I_{30}) (Morgan, 2005; Renard et al., 1997). Due to the detailed data requirements for the standard R/USLE calculation of rainfall erositivity, studies in areas with less detailed data have used alternative equations depending on the temporal resolution and availability of the rainfall data. These compiled studies have used long-term datasets with at least daily temporal resolution to construct their R-factor equation. Extensive work by Naipal et al. (2015) attempted to apply the R/USLE at a coarse global scale (30 arcsecond) by using USA and European databases to derive rainfall erosivity equations. These equations use a combination of annual precipitation (mm), mean elevation (m), and simple precipitation intensity index (mm day^{-1}) to calculate the R-factor for different Köppen-Geiger climate classifications (Naipal et al., 2015). Loureiro and Coutinho (2001) used 27 years of daily rainfall data from Portugal and the R/USLE method of calculating EI_{30} to construct an equation that uses the number of days that received over 10.0 mm of rainfall and the amount of rainfall per month when the day's rainfall exceeded 10.0 mm. The Loureiro and Coutinho (2001) equation was modified by Shamshad et al. (2008) using long-term rainfall data in Malaysia and used to construct a regression equation relating monthly rainfall and annual rainfall with the R-factor. The equation was modified because the original Loureiro and Coutinho (2001) equation was developed in Portugal, and the aim of Shamshad et al. (2008) was to modify it to suit the climatic conditions of tropical Malaysia. Similarly, Sholagberu et al. (2016) used 23 years of daily rainfall data to create a regression equation relating annual rainfall and the R-factor for the highlands of Malaysia. These equations that use monthly or annual rainfall are valuable in study areas that do not have long-term detailed rainfall data, but have a similar climate. The imperial units of erosivity are in hundreds of foot tonf inch acre^{-1} hour^{-1} year^{-1}, and multiplying by 17.02 will give the SI units of megajoule millimetre hectare^{-1} hour^{-1} year^{-1} (Renard et al., 1997).

With the body of work that has been done in rainfall erosivity, some studies have managed to construct rainfall erosivity maps over large countries and regions. Panagos et al. (2017) have used pluviographic data from 63 countries to calculate rainfall erosivity and spatially interpolated the results to construct a global rainfall erosivity map at 30 arc-seconds resolution. Despite its coarse resolution, this global dataset can be used as a resource for rainfall erosivity in data-sparse regions. For the United States, Renard et al. (1997) details the procedure for obtaining rainfall erosivity values from their large national database. Renard et al. (1997) would be the recommended reference for study areas in the United States because of the extensive database that already exists for that country. For the European Union, Panagos et al. (2015d) constructed a rainfall erosivity map at 1km resolution and published descriptive statistics for R-values in each of the member countries. The interpolated map showed good agreement through cross-validation and to previous studies, but areas that had less rainfall stations and more diverse terrain caused higher prediction uncertainty (Panagos et al., 2015d). A review of rainfall erosivity in Brazil used a large rainfall dataset with R-factors from different locations to a spatially interpolated map of rainfall erosivity, and the observed trends in the map agreed with previous work on rainfall erosivity the country (da Silva, 2004).

In areas that only have annual precipitation available, several equations and their studies can be used as a reference. In their global application, Naipal et al. (2015) published different R-factor equations depending on a study area's climate classification. One caveat is that the data for these equations had a large percentage of USA and European records, so resulting accuracy of R-factors might be better for those locations (Naipal et al., 2015). In tropical areas such as Southeast Asia, the R-factor by El-Swaify et al. (1987) as cited in Merritt et al. (2004) was used extensively in Thailand, the Philippines, and Sri Lanka. However, the units for the R-factor in this equation are given as tons hectare^{-1} year^{-1}, which do not correspond to the original units used by R/USLE (Merritt et al., 2004). This lack of consistency regarding units is not uncommon in the reviewed literature, which sometimes fails to explicitly report the units used for the different factors. For example, Renard & Freimund (1994) report that the units of R-factor equations by Arnoldus (1977) were presumed to be in metric units. By being clear and consistent about units in R/USLE literature, future researchers can be more certain about the accuracy of their borrowed R-factor equations instead of presuming the units to be the same as the original R/USLE. Work by Bonilla & Vidal (2011) produced an R-factor equation for Chile and published erosivity values similar to those produced by work in areas of similar geography and geology. For New Zealand, Klik et al. (2015) proposed equations for calculating the annual R-factor and seasonal R-factor with coefficients that change depending on the study area's location within the country.

The usage of monthly precipitation data to determine the R-factor is due to monthly data being more readily available compared to detailed storm records (Renard & Freimund, 1994). Renard & Freimund (1994) used data from 155 stations with known R-factors based on the original USLE approach and related their R-factors to observed annual and monthly precipitation. These equations developed by Renard & Freimund (1994) in the west coast of USA were used in Ecuador (Ochoa-Cueva et al., 2015), and Honduras and El Salvador (Kim et al., 2005). Work by Arnoldus (1980) developed R-factor equations in West Africa that use monthly and annual precipitation. However, these equations present a problem in terms of consistent units, as reported by Renard & Freimund (1994) in their review of previous R-factor work. In Southeast Asia, Shamsad et al. (2008) developed an R-factor equation in Malaysia that was used in the Philippines by Delgado & Canters (2012). In New Zealand, the monthly precipitation can be aggregated to seasonal precipitation and used in the equation for seasonal R-factor derived by Klik et al. (2015).

Monthly or better precipitation records are very useful in R/USLE applications because of the option of estimating soil loss at a monthly or seasonal scale, which can be useful in countries with high temporal variation of rainfall throughout the year.

Klik et al. (2015) emphasised the need to understand the drivers of soil erosion, including whether rainfall intensity had a stronger effect compared to mean annual rainfall. In an assessment of spatial and temporal variations in rainfall erosivity over New Zealand, December and January were associated with higher erosivities while August was associated with lowest erosivity (Klik et al., 2015). Similar work by Diodato (2004) has cited the use of monthly erosivity data to be more useful with respect to managing crop growing cycles and tillage practices, especially during seasons where high rainfall erosivity is expected. In locations where there is a large temporal variation in rainfall throughout the year, the seasonal approach of estimating soil erosion is more important for sustainable land management (Ferreira & Panagopoulos, 2014).

As an example of how R-factor equations can give differents estimates of rainfall erosivity, the equations by Klik et al. (2015) developed in New Zealand, Loureiro and Coutinho (2001) developed in Portugal, and Ferreira and Panagopolous (2014) also developed in Portugal were used to estimate annual and seasonal erosivity in the Mangatarere watershed (Figure 1, Table 1, and Table 2). The Mangatarere watershed (~157km^2) in New Zealand has forested areas in the hill country, and agricultural activity such as dairy and drystock farming in the plains area. For the same set of rainfall data, the three equations predicted different annual and seasonal values of erosivity. Regarding seasonal patterns of erosivity, Klik et al. (2015) predicted highest erosivity occurring during summer but lowest in winter and spring. This trend matches the national observations of the most erosive storms occur during summer, and the lowest occurring during winter (Klik et al., 2015). By contrast, both Loureiro & Coutinho (2001) and Ferreira & Panagopolous (2014) predicted highest erosivity during spring and lowest during summer. These differences highlight the importance of understanding the regional applicability of rainfall erosivity equations.

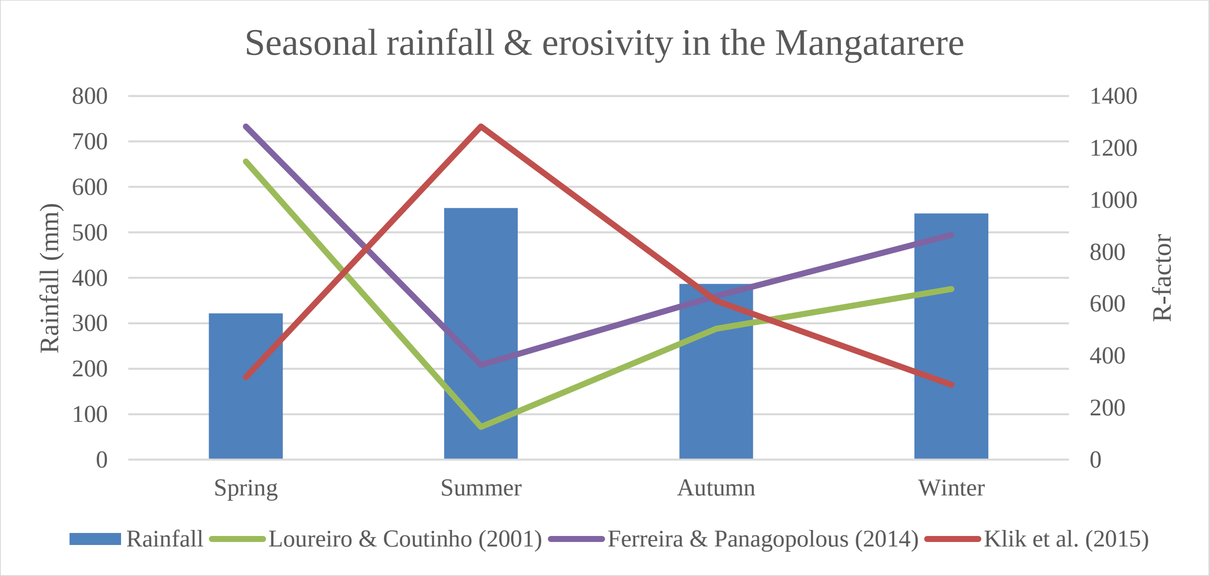

Figure 1. Graph of seasonal rainfall and estimates of erosivity in the Mangatarere.

Table 1. Annual estimates of erosivity in the Mangatarere (MJ mm ha^{-1} h-1 yr^{-1}).

Equation Source	**Klik et al. (2015)**	**Loureiro & Coutinho (2001)**	**Ferreira & Panagopolous (2014)**
Annual erosivity	2607	1391	1715

Table 2. Seasonal rainfall and estimates of erosivity in the Mangatarere (MJ mm ha^{-1} h^{-1} yr^{-1}).

Season	**Rainfall**	**Klik et al. (2015)**	**Loureiro & Coutinho (2001)**	**Ferreira & Panagopolous (2014)**
Spring	322	317	656	733
Summer	553	1283	72	208
Autumn	386	611	288	360
Winter	541	288	375	494

Table 3. Summary of different studies that developed rainfall erosivity equations, original locations, and other studies that used their equations.

#	**Author**	**Original Location**	**Resolution**	**Equation and requirements**	**Other studies**
1	Wischmeier and Smith (1978) and Renard et al. (1997)	United States of America	Sub-daily	$R = \frac{\sum_{i=1}^{j}(EI_{30})_i}{N}$ $EI_{30} = E \times I_{30}$ $E = 916 + 331 \times log_{10}$ I I = intensity (in/hr) EI_{30i} = EI_{30} for storm i j = number of storms in an N-year period Units Imperial: Hundreds of foot • tonf • inch • acre^{-1} • hour^{-1} • year-1 Metric (multiply by 17.02): Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1}	Applied around USA
2	Mihara (1951) and Hudson (1971) as cited in David (1988)	USA	Daily	$R = A \times \sum_{1}^{n} P_i^m$ A = 0.002 M = 2 P_i = Precipitation total for day *i* when *P* exceeds 25mm Units: Not specified, likely to be original USLE imperial units	Watersheds around the Philippines (David, 1988)
3	Arnoldus (1980) as cited in Renard and Freimund (1994)	Morocco and other locations in West Africa	Monthly and annual	West Africa $R = 4.79MFI - 142$ $R = 5.44MFI - 416$ Eastern USA $R = 6.86MFI - 420$ Western USA	Morocco Turkey (Demirci & Karaburun, 2012); Morocco (Raissouni et al., 2016)

				$R = 4.79MFI - 143$ Northwest USA $R = 0.66MFI - 3$ $MFI = \sum_{i=1}^{12} \frac{P_i^2}{P}$ MFI = Modified Fournier's Index P_i = monthly precipitation P = annual precipitation Units: Ton-metre • centimetre • hectare^{-1} • hour^{-1} • year^{-1} (Renard and Freimund, 1994)	
4	Renard and Freimund (1994)	West coast of USA	Monthly and annual	$R = 0.0483 \times P^{1.610}$ $R = 587.8 - 1.219P + 0.004105P^2$ Using MFI (Arnoldus, 1980): $R = 0.07397 \times MFI^{1.847}$ $R = 95.77 - 6.081MFI + 0.4770MFI^2$ P_i = monthly precipitation P = annual precipitation Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1}	Central America (Kim et al., 2005) Iran (Zakerinejad & Maerker, 2015) Ecuador (Ochoa-Cueva et al., 2015)
5	Zhou et al. (1995) as cited in Li et al. (2014)	Southern China	Monthly	$R = \sum_{i=1}^{12} -1.15527 + 1.792P_i$ P_i = monthly precipitation Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1}	China (Li et al., 2014)
6	Roose (1975) and Morgan (1974) as cited in Morgan (2005)	Peninsular Malaysia and Africa	Annual	Africa (Roose, 1975): $R = 0.5 \times P \times 17.3$ Peninsular Malaysia: $R = (9.28 \times P - 8838)\left(\frac{75}{1000}\right)$ P = mean annual precipitation (mm) Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1}	Malaysia (Roslee et al., 2017); Vanuatu (Dumas & Fossey, 2009); Iran (Zakerinejad & Maerker, 2015)
7	El-Swaify et al. (1987) as cited in Merritt et al. (2004)	Possibly Thailand	Annual	$R = 38.5 + 0.35P$ P = mean annual precipitation Units: Tons • hectare^{-1} • year^{-1} (All the other factors must have been developed to have no units so that the final soil loss is in tons/ha/year)	Thailand (Eiumnoh, 2000; Merritt et al., 2004); Philippines (Adornado & Yoshida, 2010; Adornado et al., 2009; Hernandez et al., 2012); Sri Lanka (Jayasinghe et al.,

					2010)
8	Land Development Department (2000), as cited in Nontananandh and Changnoi (2012)	Thailand	Annual	$R = 0.04669P - 12.1415$ P = mean annual rainfall Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1}	Thailand (Nontananandh & Changnoi, 2012)
9	Loureiro and Coutinho (2001)	Portugal	Daily	$R = \frac{1}{N}\sum_{i=1}^{N}\sum_{m=1}^{12} EI_{30(monthly)}$ $EI_{30\,(monthly)} = 7.05rain_{10} - 88.92days_{10}$ Rain$_{10}$ = monthly rainfall for days with ≥ 10.0mm of rain Days$_{10}$ = monthly number of days with rainfall ≥ 10.0mm of rain N = number of years Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1}	Spain (López-Vicente, Navas, & Machín, 2008)
10	Fernandez et al. (2003), originally developed by the USDA-ARS (2002)	USA	Annual	$R = -823.8 + 5.213P$ P = annual precipitation Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1}	USA (Fernandez et al., 2003); Greece (Jahun et al., 2015)
11	Ram et al. (2004), as cited in Jain and Das (2010)	India	Annual	$R = 81.5 + 0.38P$ P = annual precipitation for areas where annual precipitation ranges between 340mm to 3500mm Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1}	India (Jain & Das, 2010)
12	Shamshad et al. (2008)	Malaysia	Monthly and annual	Based on Loureiro and Coutinho (2001) but for Malaysia: $R = \sum_{i=1}^{12} 6.97rain_{10} - 11.23days_{10}$ $R = \sum_{i=1}^{12} 0.266 \times rain_{10}^{2.071} \times days_{10}^{-1.367}$ $R = \sum_{i=1}^{12} 227 \times \left(\frac{P_i^2}{P}\right)^{0.548}$ Rain$_{10}$ = monthly rainfall for days with ≥ 10.0mm of rain Days$_{10}$ = monthly number of days with rainfall ≥ 10.0mm of rain P$_i$ = monthly precipitation P = annual precipitation	Philippines (Delgado & Canters, 2012)

13	Irvem et al. (2007)	Turkey	Monthly and annual	Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1} $R = 0.1215 \times MFI^{2.2421}$ $MFI = \sum_{i=1}^{12} \frac{P_i^2}{P}$ P_i = monthly precipitation P = annual precipitation	Turkey (Ozsoy et al., 2012)
14	Ferreira and Panagopolous (2014), similar to Loureiro and Coutinho (2001)	Portugal	Daily	Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1} $R = \sum_{i=1}^{12} 6.56 rain_{10} - 75.09 days_{10}$ $Rain_{10}$ = monthly rainfall for days with $\geq$ 10.0mm of rain $Days_{10}$ = monthly number of days with rainfall $\geq$ 10.0mm of rain	Portugal (Ferreira & Panagopoulos, 2014)
15	Nakil (2014) as cited in Nakil and Khire (2016)	India	Annual	Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1} $R = 839.15 \times e^{0.0008P}$ P = annual precipitation	India (Nakil & Khire, 2016)
18	Naipal et al. (2015)	Global application, but original data from USA and Europe	Annual	Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1} Various equations depending on Köppen climate classification, including alternate equations if SDII is not available P = annual precipitation (mm) Z = mean elevation (m) SDII = simple precipitation intensity index (mm day^{-1})	
19	Klik et al. (2015)	New Zealand	Annual or seasonal	Annual or seasonal: $R = aP^b$ $R = aP + b$ P = annual precipitation (mm) or seasonal precipitation (mm) a & b = constants depending on region of New Zealand The equation used will depend on the region of New Zealand, and the season.	
20	Sholagberu et al. (2016)	Malaysia	Annual	Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} $R = 0.0003P^{1.771}$ P = annual precipitation	

	Units: Megajoule •millimetre • hectare^{-1} • hour^{-1} • year^{-1}

2.2 Soil erodibility factor (K)

The K-factor represents the influence of different soil properties on the slope's susceptibility to erosion (Renard et al., 1997). It is defined as the "mean annual soil loss per unit of rainfall erosivity for a standard condition of bare soil, recently tilled up-and-down slope with no conservation practice" (Morgan, 2005). The K-factor essentially represents the soil loss that would occur on the R/USLE unit plot, which is a plot that is 22.1m long, 1.83m wide, and has a slope of 9% (Lopez-Vicente et al., 2008).

Higher K-factor values indicate the soil's higher susceptibility to soil erosion (Adornado et al., 2009). In the R/USLE, Wischmeier and Smith (1978) and Renard et al. (1997) use an equation that relates textural information, organic matter, information about the soil structure and profile-permeability with the K-factor or soil erodibility factor. However, other soil classifications might not include soil structure and profile-permeability information that matches the information required by R/USLE nomograph. Hence, alternative equations have been developed that exclude the soil structure and profile-permeability (Table 4). The question of which equation to use depends on the availability of soil data. Where only the textural class and organic matter content is known, Stewart et al. (1975) have approximated K-factor values based on these inputs. Similar to the R-factor, the imperial units of soil erodibility are in ton acre hour hundreds of acre^{-1} foot^{-1} tonf^{-1} inch^{-1}, and multiplying by 0.1317 gives the erodibility in SI units of metric ton hectare hour hectare^{-1} megajoule^{-1} millimetre^{-1} (Renard et al., 1997).

Although seemingly relatively straightforward, the K-factor equation proposed by Wischmeier and Smith (1978) comes with a few limitations regarding soil type. This equation was developed using data from medium-textured surface soils in the Midwestern USA, with an upper silt fraction limit of 70% (Renard et al., 1997). An equation for volcanic soils in Hawaii was proposed by El-Swaify & Dangler (1976) as cited in Renard et al. (1997), but is only appropriate for soils similar to Hawaiian soils and not for all tropical soils. Despite these limitations, many studies outside the USA have used the original Wischmeier & Smith (1978) K-factor equation (Table 4). Being aware of the regional specificity of K-factor equations is important, and using different K-factor equations in one study area to find a range of soil erodibility could be a way of testing their applicability.

Table 4. Summary of different studies with soil erodibility equations, original locations, and other studies that used their equations. All of the equations in Table 2 use imperial units of soil erodibility: ton • acre • hour • hundreds of acre^{-1} • foot^{-1} • tonf^{-1} • inch^{-1}. Multiply by 0.1317 to give in SI units of metric ton • hectare • hour • hectare^{-1} • megajoule^{-1} • millimetre^{-1}.

#	Author	Original Location	Data requirements	Equation	Other studies
1	Wischmeier and Smith (1978) and	USA	Very fine sand (%), clay (%), silt	$M = Silt \times (100 - Clay)$	Thailand (Eiumnoh, 2000); Vanuatu

	Renard et al. (1997)		(%), organic matter (%), soil structure, profile-permeability	$K = \{[2.1 \times M^{1.14} \times (10^{-4}) \times (12 - a)] + [3.25 \times (b - 2)] + [2.5 \times (c - 3)]\} \div 100$ M = Particle-size parameter Silt = Silt (%) but also includes the percentage of very fine said (0.1 to 0.05mm) Clay = Clay (%) a = Organic matter (%) b = Soil-structure code used in soil classification: • 1: Very fine granular • 2: Fine granular • 3: Medium or coarse granular • 4: Blocky, platy, or massive c = Profile-permeability class • 1: Rapid • 2: Moderate to rapid • 3: Moderate • 4: Slow to moderate • 5: Slow • 6: Very slow	(Dumas & Fossey, 2009); Philippines (Schmitt, 2009); India (Jain & Das, 2010); Turkey (Ozsoy et al., 2012); Iran (Bagherzadeh, 2014); Portugal (Ferreira & Panagopoulos, 2014); China (Li et al., 2014); European Union (Panagos et al., 2014)
2	Williams and Renard (1983) as cited in Chen et al. (2011)	USA	Sand (%), silt (%), clay (%), organic carbon (%)	$K = 0.2 + 0.3\exp\left(0.0256 \times Sa \times \left(1 - \frac{Si}{100}\right)\right) \times \left(\frac{Si}{Cl + Si}\right)^{0.3} \times \left(1.0 - \frac{0.25 \times C}{C + \exp(3.72 - 2.95C)}\right) \times \left(1.0 - \frac{0.7 \times SN}{SN + \exp(-5.51 + 22.9SN)}\right)$ Sa = Sand % Si = Silt % Cl = Clay % SN = 1-(Sa/100) C = Organic Carbon	China (Chen et al., 2011)
3	David (1988), a simplified version of Wischmeier and Mannering (1969)	USA	Sand (%), clay (%), silt (%), organic matter (%), pH	$K = [(0.043 \times pH) + (0.62 \div OM) + (0.0082 \times S) - (0.0062 \times C)] \times Si$ pH = pH of the soil OM = Organic matter in percent S = Sand content in percent C = Clay ratio = % clay / (% sand + % silt) Si = Silt content = % silt / 100	Philippines (David, 1988; Hernandez et al., 2012)
4	El-Swaify & Dangler (1976) as cited in Renard et al. (1997)	Hawaii, USA	Textural information, base saturation	$K = -0.03970 + 0.00311x_1 + 0.00043x_2 + 0.00185x_3 + 0.00258x_4 - 0.00823x_5$ x_1 = unstable aggregate size fraction (<0.250mm) (%) x_2 = modified silt (0.002 - 0.1mm) (%) * modified sand (0.1 - 2mm) (%)	

x_3 = % base saturation
x_4 = silt fraction (0.002 - 0.050mm) (%)
x_5 = modified sand fraction (0.1 - 2mm) (%)

2.3 Slope length (L) and steepness (S) factor

The LS-factor represents the effect that the slope’s length and steepness affect sheet, rill, and inter-rill erosion by water, and is the ratio of expected soil loss from a field slope relative to the original USLE unit plot (Wischmeier & Smith, 1978). The USLE method of calculating the slope length and steepness factor was originally applied at the unit plot and field scale, and the RUSLE extended this to the one-dimensional hillslope scale, with different equations depending on whether the slope had a gradient of more than 9% (Renard et al., 1997; Wischmeier & Smith, 1978). Further research extends the LS-factor to topographically complex units using a method that incorporates contributing area and flow accumulation (Desmet & Govers, 1996). The USLE and RUSLE method of calculating the LS-factor uses slope length, angle, and a parameter that depends on the steepness of the slope in percent (Wischmeier & Smith, 1978).

However, one of the criticisms of the original USLE method of calculating LS-factor is its applicability to more complex topography. With advances in GIS technology, the method of determining the LS-factor as a function of upslope contributing area or flow accumulation and slope has risen in popularity (Table 5). The use of digital elevation models (DEMs) to calculate upslope contributing area and the resulting LS-factor allows researchers to account for more topographically complex landscapes (Moore & Burch, 1986; Desmet & Govers, 1996). Desmet and Govers (1996) have also built on this method through showing its application in a GIS environment over topographically complex terrain when compared to the original method proposed by Wischmeier and Smith (1978). This method of using flow accumulation for slope length and steepness explicitly accounts for convergence and divergence of flow, which is important when considering soil erosion over a complex landscape (Wilson & Gallant, 2000). It is possible to use this method to calculate the LS-factor over a large extent, but a high resolution DEM is needed for accurate representation of the topography. In their application of R/USLE over the geographic extent of the European Union, Panagos et al. (2015a) used a 25 m DEM because of associated loss of detail regarding network flow patterns in coarser resolution DEMs (100 m).

The original equations for LS-factor assume that slopes have uniform gradients and any irregular slopes would have to be divided into smaller segments of uniform gradients for the equations to be more accurate (Wischmeier & Smith, 1978). At the plot or small field scale, this manual measurement of slopes and dividing into segments may be manageable, but less useful at larger scales. In terms of practicality, Desmet & Govers (1996) have reported studies of this method applied at a watershed scale with the disadvantages of it being time-consuming. Studies in Iran and the Philippines have implemented the R/USLE methods within a GIS environment by calculating the LS-factor for each raster cell in a DEM, essentially treating each pixel as its own segment of uniform slope (Bagherzadeh, 2014; Schmitt, 2009).

As explained above, the method of using flow accumulation, upslope contributing area, and slope in a GIS environment has gained popularity due to its ability to explicitly account for convergence and divergence of flow, thus capturing more complex topography (Wilson & Gallant, 2000). This method was applied at the scales of watersheds and regions (as shown in **Table 5**) and has even been applied by Panagos et al. (2015a) at the scale of the European Union using a 25m DEM. The only thing really limiting users is the availability of high-resolution DEMs and the trade-off between processing time and accuracy. The original R/USLE methods require only slope angle and length, operates over a single cell in a DEM by treating it as a uniform slope, and would take less processing time compared to the method using flow accumulation. However, the user must remember that this cannot capture the convergence and divergence of flow and thus sacrifices accuracy for time.

Table 5. Summary of methods of calculating LS-factor, original locations, and other studies that used these methods.

#	Author	Original Location	Data requirements	Equation	Other studies that utilised similar methods
1	Wischmeier and Smith (1978)	USA	Slope length and angle	$LS = (\frac{\lambda}{72.6})^m \times [(65.41 \times \sin^2\theta) + (4.56 \times \sin\theta) + 0.065]$ λ = Slope length in feet ϴ = Angle of slope m = Dependent on the slope • 0.5 if slope > 5% • 0.4 if slope is between 3.5% and 4.5% • 0.3 if slope is between 1% and 3% • 0.2 if slope is less than 1%	Thailand (Eiumnoh, 2000; Merritt et al., 2004); Vanuatu (Dumas & Fossey, 2009); Iran (Bagherzadeh, 2014)
2	Renard et al. (1997)	USA	Slope length and angle	$L = \left(\frac{\lambda}{72.6}\right)^m$ $m = \frac{\beta}{1 + \beta}$ $\beta = \frac{(\frac{\sin\theta}{0.0896})}{[3.0 \times (\sin\theta)^{0.8} + 0.56]}$ If slope is less than 9%: $S = 10.8 \times \sin\theta + 0.03$ If slope is greater or equal to 9%: $S = 16.8 \times \sin\theta - 0.50$ But if the slope is shorter than 15 feet: $S = 3.0 \times (\sin\theta)^{0.8} + 0.56$ λ = Slope length in feet ϴ = Angle of slope m = Dependent on the slope • 0.5 if slope > 5% • 0.4 if slope is between 3.5% and	Philippines (Schmitt, 2009); China (Li et al., 2014); Thailand (Nontananandh & Changnoi, 2012); Turkey (Ozsoy et al., 2012)

				4.5% • 0.3 if slope is between 1% and 3% • 0.2 if slope is less than 1%	
3	David (1988), based on work by Madarcos (1985) and Smith & Whitt (1947)	Philippines, but based on work from the USA	Slope rise in percent	$LS = a + b \times S_L^{4/3}$ a = 0.1 b = 0.21 S_L = Slope in percent	Philippines (David, 1988)
4	Morgan (2005) but previously published in earlier editions	Britain	Slope length and gradient in percent	$LS = \left(\frac{l}{22}\right)^{0.5} (0.065 + 0.045s + 0.0065s^2)$ l = slope length (m) s = slope steepness (%)	India (Nakil & Khire, 2016; Sinha & Joshi, 2012); Greece (Rozos et al., 2013)
5	Moore & Burch (1986) as cited in Mitasova et al. (1996); Desmet & Govers (1996); Mitasova et al. (2013);	USA	Upslope contributing area per unit width, which can be approximated through flow accumulation, cell size, slope	$LS = (m+1)\left(\frac{U}{L_0}\right)^m \left(\frac{\sin\beta}{S_0}\right)^n$ U (m^2m^{-1}) = upslope contributing area per unit width as a proxy for discharge $U = Flow\ Accumulation \times Cell\ Size$ L_0 = length of the unit plot (22.1) S_0 = slope of unit plot (0.09) β = slope m (sheet) and n (rill) depend on the prevailing type of erosion (m= 0.4 to 0.6) and n (1.0 to 1.3)	Philippines (Adornado & Yoshida, 2010; Adornado et al., 2009); Sri Lanka (Jayasinghe et al., 2010); China (Chen et al., 2011); Iran (Zakerinejad & Maerker, 2015); Jordan (Farhan & Nawaiseh, 2015); Morocco (Raissouni et al., 2016); New Zealand (Fernandez & Daigneault, 2016) Similar methods from Moore & Burch (1986): India (Jain & Das, 2010); Portugal (Ferreira & Panagopoulos, 2014); Greece (Jahun et al., 2015); India (Nakil & Khire, 2016) Similar methods from Desmet & Govers (1996): USA (Boyle et al., 2011); Turkey (Demirci & Karaburun, 2012); Philippines (Delgado & Canters, 2012)

2.4 Cover and management factor (C)

The cover and management factor (C) is defined as the ratio of soil loss from a field with a particular cover and management compared to a field under "clean-tilled continuous fallow" (Wischmeier & Smith, 1978). The R/USLE uses a combination of sub-factors such as impacts of previous management, canopy cover, surface cover and roughness, and soil moisture on potential erosion to produce a value for soil loss ratio, which is used with R-factor to produce a value for C-factor (Renard et al., 1997). This method requires extensive knowledge of the study area's cover characteristics including agricultural management and may be suitable at field or farm scale, but monitoring all these characteristics at the watershed scale may not be feasible.

A simpler method of determining the C-factor is referencing studies that have reported values for similar land cover, or from studies done in the same area or region. Table 7 and Table 8 give a broad overview of C-factors for different cover types and common crops. Wischmeier & Smith (1987) also include the effect of percent ground cover, reporting C-factor values for the same cover type over a range of cover percentage and condition. Morgan (2005) and David (1988) have reported values for the different growth stages of the same types of trees. A simple method of creating a C-factor layer us by using lookup tables to assign C-factor values to the land cover classes present in the study area. When using C-factors from literature, it is important to note the definition of land cover type between two countries may vary. For example, land classified as forest in one country may be different in terms of vegetation cover or type compared to forest in another country (e.g. differences in pine forests and tropical forests). Therefore, it is crucial to understand the differences between land cover classifications before applying C-factor values from literature. Van der Knijff et al. (2000) cites the large spatial and temporal variations in cover and crop over a large region such as the European Union as another reason why using the lookup table-based approach is inadequate and tedious.

To address this, another method of determining the C-factor is through the Normalized Difference Vegetation Index (NDVI) that estimated from satellite imagery. Although there are NDVI layers available, these are limited by: geographical coverage, date of acquisition, and resolution. The MODIS NDVI dataset made by Caroll et al. (2004) at 250m resolution covers the USA and South America (http://glcf.umd.edu/data/ndvi/). NASA produced a global dataset of NDVI values at 1-degree resolution for the timespan of July 1983 to June 1984, making it suitable for studying historical soil erosion but not necessarily for the current state of land cover (https://data.giss.nasa.gov/landuse/ndvi.html).

In areas where ready-made NDVI products are unavailable, authors used satellite imagery to obtain NDVI such as AVHRR or Landsat ETM (Van der Knijff et al., 2000; De Asis & Omosa, 2007; Ma et al., 2001 as cited in Li et al., 2014). De Asis & Omasa (2007) related C-factor and NDVI through fieldwork and image classification; determining C-factor at several points within the study area using the R/USLE approach and relating it to the NDVI through regression correlation analysis. For larger study areas, this may not be feasible such as in the European Union where Van der Knijff et al. (2000) determined NDVI from satellite imagery and created an equation based on its positive correlation with green vegetation (Table 6). This approach enabled them to create a C-factor map over the European Union. However, C-factors were unrealistically high in some areas such as woodland and grassland, so values for those areas were taken from literature.

An advantage of using is NDVI that researchers can determine sub-annual C-factors if there is satellite imagery available, which can lead to understanding the contribution of cover to seasonal soil erosion and identifying critical periods within the year were soil erosion is a risk (Ferreira and Panagopoulos, 2014). Similar methods have been applied in Brazil by Durigon et al. (2014), Greece by Alexandridis et al. (2015), and Kyrgyzstan by Kulikov et al. (2016). Determining C-factors at the seasonal scale is important because vegetation cover can change throughout the year due to agricultural and forestry practices. In study areas with a high temporal variation of rainfall throughout the year, seasonal vegetation can play a big part in exacerbating or mitigating soil erosion.

The choice of which method to use depends on the scale of the study area, reported C-factors for similar cover, and availability of high-resolution imagery. For small-scale studies, it is more feasible to determine the C-factors through fieldwork. If previous R/USLE studies have reported C-factors for cover similar to the study area, those values can be used for the table-based approach. Lastly, high-resolution imagery can be used to determine the study area's NDVI. At small scales and with a good understanding of differences in land cover classifications, pulling values from literature may be the most efficient choice but at larger regional scales, this may become tedious. At larger scales, high-resolution satellite imagery may be available to determine NDVI but authors must be mindful of its acquisition date in relation to their study period, and requires pre-processing such as masking cloud cover and creating aggregates from these masked images (Van der Knijff et al., 2000; Kulikov et al., 2016).

Table 6. C-factor equations that use NDVI.

#	Author	Original Location	Equation
1	Van der Knijff et al. (2000)	Europe	$C = \exp\left[-\propto\left(\frac{NDVI}{\beta - NDVI}\right)\right]$ $\alpha = 2$ $\beta = 1$
2	Ma et al. (2001) as cited in Li et al. (2014)	China	$f_g = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$ $C = \begin{cases} 1 & f_g = 0 \\ 0.6508 - 0.343 \times \log(f_g) & 0 < f_g < 78.3\% \\ 0 & f_g \geq 78.3\% \end{cases}$

Table 7. C-factors for general types of land cover compiled from various sources.

Cover	Dymond (2010) (New Zealand)	David (1989) (Philippines)	Morgan (2005) (Various)	Fernandez et al. (2003) (USA)	Dumas & Fossey (2009) (Vanuatu)	Land Development Department (2002) as cited in Nontananandh & Changnoi (2012)

Bare ground	1	1	1				
Urban		0.2		0.03	0		0
Crop				0.128	0.01	0.255–0.525	
Forest	0.005	0.001–0.006	0.001	0.001	0.001	0.003–0.048	
Pasture	0.01		0.1				
Scrub	0.005	0.007–0.9	0.01	0.003	0.16	0.01–0.1	

Table 8. C-factors for specific types of land cover compiled from various sources.

Cover	**Panagos et al. (2015b) (Europe)**	**David (1989) (Philippines)**	**Morgan (2005) (Various)**
Bananas		0.1–0.3	
Barley	0.21		
Chili			0.33
Cocoa			0.1–0.3
Coffee			0.1–0.3
Common wheat and spelt	0.2		0.1–0.4
Cotton seed	0.5	0.4–0.6	0.4–0.7
Dried pulses (legumes) and protein crop	0.32	0.3–0.5	0.04–0.7
Durum wheat	0.2		
Fallow land	0.5		
Grain maize-corn	0.38	0.3–0.6	0.02–0.9
Groundnuts			0.3–0.8
Linseed	0.25		0.1–0.2
Oilseeds	0.28		
Palm with cover crops		0.05–0.3	0.1–0.3
Pineapple		0.2–0.5	0.01–0.4
Potatoes	0.34		0.1–0.4
Rape and turnip rape	0.3		
Rice	0.15	0.1–0.2	0.1–0.2
Rye	0.2		
Soya	0.28		0.2–0.5
Sugar beet	0.34		
Sugarcane			0.13–0.4
Sunflower seed	0.32		
Tobacco	0.49	0.4–0.6	
Yams			0.4–0.5

2.5 Support practice factor (P)

The support practice factor (P) is defined as the ratio of soil loss under a specific soil conservation practice (e.g. contouring, terracing) compared to a field with upslope and downslope tillage (Renard et al., 1997). The P-factor accounts for management practices that affect soil erosion through modifying the flow pattern, such as contouring, strip-cropping, or terracing (Renard et al., 1997). The more effective the conservation practice is at mitigating soil erosion, the lower the P-factor (Bagherzadeh, 2014). Like the C-factor, values for P-factors can be taken from literature and if there are no support practices observed, the P-factor is 1.0 (Adornado et al., 2009). The P-factor can also be estimated using subfactors, but the difficulty of accurately mapping support practice factors or not observing support practices leads to many studies ignoring it by giving their P-factor a value of 1.0 as seen in Appendix 1 (Adornado et al., 2009; Renard et al., 1997; Schmitt, 2009).

Another possible reason why studies may ignore P-factor is due to the nature of their chosen C-factors. Some C-factors already account for the presence of a support factor such as intercropping or contouring. For example, Morgan (2005) and David (1989) give C-factors for one type of crop, but with different types of management.

Despite the P-factor being commonly ignored, a number of studies have reported possible P-factors for different kinds of tillage, terracing, contouring, and strip-cropping (**Table 10**). At suitably detailed scales and with enough knowledge of farming practices, using these P-factors may lead to a more accurate estimation of soil loss. Additionally, these P-factors can be used in scenario analysis to understand how changing farming practices may mitigate or exacerbate soil loss. As seen in **Table 10**, the P-factor can affect the estimated soil loss by a large factor, such as zoned-tillage giving a factor of 0.25 and thus reducing the soil loss estimate.

Table 9. Examples of where C-factor accounts for crop management from Morgan (2005) and David (1989).

Crop	Management	C-factor
Maize, sorghum or millet	High productivity; conventional tillage	0.20–0.55
	Low productivity; conventional tillage	0.50–0.90
	High productivity; chisel ploughing into residue	0.12–0.20
	Low productivity; chisel ploughing into residue	0.30–0.45
	High productivity; no or minimum tillage	0.02–0.10
Coconuts	Tree intercrops	0.05–0.1
	Annual crops as intercrop	0.1–0.30

Table 10. P-factors for different types of agricultural management practices.

	David (1988)
Tillage and Residue Management	**P-factor**
Conventional tillage	1.00
Zoned tillage	0.25
Mulch tillage	0.26
Minimum tillage	0.52

Slope (%)	Terracing		Contouring	Contour Cropping	Strip
	Bench	Broad-based			
1 – 2	0.10	0.12	0.60	0.30	

3 – 8	0.10	0.10	0.50	0.15
9 – 12	0.10	0.12	0.60	0.30
13 – 16	0.10	0.14	0.70	0.35
17 – 20	0.12	0.16	0.80	0.40
21 – 25	0.12	0.18	0.90	0.45
> 25	0.14	0.20	0.95	0.50
Panagos et al. (2015c)				
Slope (%)		Contouring P-factor		
9 – 12		0.6		
13 – 16		0.7		
17 – 20		0.8		
21 – 25		0.9		
> 25		0.95		

3 Limitations of R/USLE

The most commonly cited limitation of the R/USLE models is their applicability to regions outside of the United States of America. The original USLE was formulated based on soil erosion studies on agricultural land in the USA and when applied to different climate regimes and land cover conditions may lead to over-prediction or under-prediction of actual average annual soil loss (Kinnell, 2010). For example, the original equation for soil erodibility is less accurate for soils with high clay content, sandy loams, and soils with high organic matter (Stewart et al., 1975). Since the R/USLE parameters were developed based on studies of agricultural plots, there are uncertainties associated with using the original USLE at the catchment or regional scale (Nagle et al., 1999; Naipal et al., 2015). Improvements and modifications to the R/USLE, especially to the LS-factor as detailed in the corresponding section, have made it applicable to larger scales, including a coarse resolution at the global scale (Naipal et al., 2015).

The uncertainties from soil erosion modelling also stem from the low availability of long-term reliable data for modelling, which is a problem not unique to R/USLE applications and is more pressing for more complex models that have high data inputs (de Vente & Poesen, 2005; Hernandez et al., 2012). Its application in data-scarce regions leads to uncertainty in actual soil loss quantities, and such applications have reported erosion vulnerability as categories (low to extreme) rather than annual average amounts (Adornado et al., 2009; Schmitt, 2009). Even so, the R/USLE is seen as the first attempt at estimating soil loss for a landscape due to its relative simplicity and less data requirements (Aksoy & Kavvas, 2005).

Another frequently-cited limitation is that the R/USLE estimates soil loss through sheet and rill erosion, but not from other types of erosion such as gully erosion, channel erosion, bank erosion, or from mass wasting events such as landslides (Nagle et al., 1999; Wischmeier & Smith, 1978). By excluding these types of erosion, the R/USLE may underestimate the actual soil loss (Thorne et al., 1985). The model also does not account for deposition, leading to overestimation, or sediment routing (Desmet & Govers, 1996; Wischmeier & Smith, 1978). Since it does not predict the sediment pathways from hillslopes to water bodies, it is difficult to analyse possible effects on downstream areas, such as pollution or sedimentation (Jahun et al., 2015). These two limitations are linked to the model's representation of more topographically complex terrain, and previous studies have attempted to address it by improving on the LS-factor by incorporating upstream contributing area (Desmet & Govers, 1996; Moore et al., 1991).

Despite these drawbacks, the USLE family of models is still widely used because of is relative simplicity and low data requirements compared to more complex physically based models. Studies around the world continue to improve R/USLE parameterisation and application in different climate regimes and locations.

4 Future directions

Since the R/USLE and its family of models are used over different geographic locations and climate types, it is important for future research to build on them and improve their representation of real-world soil loss. Some of the future directions include incorporating soil loss from other types of erosion, estimating soil loss at seasonal or sub-annual temporal scales, and improving the consistency of formulae and units in the scientific literature.

4.1 Representing other types of erosion

The R/USLE accounts for rill and inter-rill erosion, but not for soil losses due to ephemeral gullies, which can lead to under-prediction of soil loss estimates (Thorne et al., 1985). In their research on improving the topographic factor in R/USLE, Desmet & Grovers (1996) recommended that delineation of ephemeral gullies combined with R/USLE could improve the identification of vulnerable areas within a watershed. These ephemeral gullies are small channels that form due to the erosive action of overland flow during a rainfall event (Momm et al., 2012). One of the studies referenced by Desmet & Govers (1996) was work by Thorne et al. (1985) and the compound topographic index (CTI). This CTI is not to be confused with the CTI formulated by Beven and Kirkby (1979), which is used within TOPMODEL (a watershed model) to identify source areas for saturation overland flow and runoff that may cause soil erosion (Aksoy & Kavvas, 2005; Beven & Kirkby, 1979). Both indices utilise contributing area and slope, but the objective of Beven and Kirkby (1979) was to use topographic analysis to derive a relationship between basin storage and contributing area in order to predict basin response. On the other hand, the objective of Thorne et al. (1985) was to use topographic analysis to predict locations of ephemeral gullies based on upstream drainage area, slope, and the planform curvature.

Topography has a large influence on the spatial aspects watershed hydrology through its effects on soil moisture distribution and flow (Sørensen et al., 2006). In the USLE, the topography is accounted for in the LS-factor which is a function of slope length and steepness, which affects the rate of soil erosion due to water (Wischmeier & Mannering, 1968). Since the USLE was originally designed at the plot scale, its use causes issues when used at larger scales with more complex topography. R/USLE compensates for this by using a Geographic Information System (GIS) method of determining runoff contribution from upstream areas to downstream locations (de Mello et al., 2016). A common criticism of R/USLE is the exclusion of sediment yields from gully, streambank, and streambed erosion. Gully erosion can contribute a significant amount of sediment loss, such as 11,000 t km^{-2} yr^{-1} in the Waipaoa catchment in New Zealand (Basher, 2013). By only considering rill and inter-rill erosion through R/USLE, potential soil loss may be underestimated, hence the importance of adding gully erosion to the model (Thorne et al., 1985).

Similar work combining the effect of rill and sheet erosion with gully erosion was done by Momm et al. (2012) in Kansas, and by Zakerinejad and Maeker (2015) in the Mazayjan watershed in Iran. Momm et al. (2012) combined several types of erosion: sheet and rill, gully, and bed and bank erosion, with the sheet and rill erosion estimated using the R/USLE model. They used varying critical CTI thresholds to iteratively generate potential locations of ephemeral gullies, identify sub-watersheds prone to gully erosion, and use scenario analysis to estimate reductions in sediment yields under conservation practices (Momm et al., 2012). One of the limitations Momm et al. (2012) identified was of DEM size; since ephemeral gullies are small features (few metres wide, ~25cm deep), higher-resolution DEMs and LiDAR data would be better for topographic analysis. Another limitation was that topography is only one contributing factor to gully formation, and being able to include the effects of vegetation cover and soil properties could help improve the procedure (Momm et al., 2012). The Unit Stream Power Erosion Deposition Model (USPED), which is similar to the R/USLE model, has also been used to estimate rill and sheet erosion rates with a stream power index (SPI) approach to estimate gully erosion rates (Zakerinejad & Maerker, 2015). Zakerinejad & Maerker (2015) estimated gully erosion in tons hectare^{-1} year^{-1} and combined it with the estimates from the USPED model to produce a map showing potential erosion and deposition within their study area. Hence, there is indeed a precedent and a need to combine erosion estimates from R/USLE with a procedure that accounts for gully erosion for more effective land management.

4.2 Seasonal erosion vulnerability

R/USLE applications usually estimate soil loss at the annual timescale, and the MUSLE estimates soil loss from a single storm event (Renard et al., 1997; Sadeghi et al., 2014). As seen in the review of methods to calculate rainfall erosivity, many different studies have attempted to estimate the R-factor, underscoring its importance to soil erosion research. However, estimating the R-factor at the annual timescale does not account for seasonal variations in rainfall. It is useful for land management to understand seasonal variations in soil erosion vulnerability because of the dual effect of rainfall and land cover on soil loss, and the effect of rainfall on land cover (Kulikov et al., 2016). For example, when a season of heavy rainfall coincides with low vegetation cover, the risk of soil erosion increases considerably (Ferreira & Panagopoulos, 2014). Thus, most of the studies around seasonal estimations of soil loss revolve around changes in land cover and rainfall. The soil erodibility (K-factor) can vary too due to changes in permeability and the effects of freezing and thawing, but it is less frequently studied compared to variations in land cover and rainfall (López-Vicente et al., 2008).

Studies that incorporate seasonality in the R/USLE commonly compute R-factors and C-factors at monthly or seasonal time scales. Lu & Yu (2002) computed monthly R-factors in Australia, which was then used in a later study that computed C-factors based on satellite imagery and the NDVI, to produce monthly maps of soil erosion vulnerability over the entire Australian continent (Lu et al., 2003; Lu & Yu, 2002). The method of estimating C-factors using NDVI is popular due to the available of remotely-sensed imagery, and the capability of processing datasets with relative expedience compared to time-consuming fieldwork. Other studies have used the NDVI and similar characteristics to estimate monthly and seasonal C-factors in Brazil, Greece, and Kyrgyzstan (Alexandridis et al., 2015; Durigon et al., 2014; Ferreira & Panagopoulos, 2014; Kulikov et al., 2016; Panagos et al., 2012). The C-factors can also be estimated monthly through the method recommended by R/USLE, but requires knowledge of prior land use, canopy cover, surface roughness, and soil moisture (López-Vicente et al., 2008).

Monthly or seasonal estimations of rainfall factors are more useful to land management planning around crop growth cycles and tillage practices (Diodato, 2004). Studies have used different methods to calculate R-factors, with data requirements ranging from per-storm basis to annual averages. To estimate monthly and seasonal estimations, the required rainfall data can be as fine as individual storm intensity to use the R/USLE method, or be as coarse as average monthly rainfall. Diodato (2004) in Italy and Kavian et al. (2011) used the R/USLE method to calculate storm energy and summed these up per month and season to obtain R-factors. Other studies used daily and monthly rainfall to calculate monthly R-factors and combine them for seasonal R-factors (Alexandridis et al., 2015; Kavian et al., 2011; López-Vicente et al., 2008; Lu et al., 2003; Panagos et al., 2015d; Shamshad et al., 2008). The results of these studies focused on identifying high and low periods of the landscape's vulnerability to soil erosion, depending on combinations of rainfall intensity and land cover.

At the baseline scenario, applying the R/USLE can give management an idea of which areas are vulnerable to soil erosion. Previous work by Alexandridis et al. (2015) and Ferreira & Panagopoulos (2014) have looked at seasonal variations in soil loss due to land cover using satellite imagery from different times of the year. These approaches are useful in determining soil loss based on previous or existing land cover, but the next step is using scenario analysis to help land management. Scenario analysis can include a myriad of options: expanded urban areas or development, changing crop rotation cycles, or applying support practices in steep or upland areas. By adding seasonal effects, it gives additional knowledge of when these vulnerable areas may be even more vulnerable. Thus, by using scenario analysis, management can test different types of crop and support practices to see their possible effect on soil erosion mitigation. Soil erosion also affects water quality because of sediment delivery to streams and rivers, which raises concerns about access to clean water for drinking and for recreational use. Therefore, understanding seasonal soil erosion is beneficial to local government who can address potential sources of sediment delivery before the problem occurs and be more proactive in their land management.

4.3 Consistency in units

The USLE was originally developed using imperial units and although the handbook provides conversion factors to convert to metric, there are still issues within the scientific literature regarding units. In the process of this review, it was noted that although most studies used the metric units for R-factor and K-factor, there were other studies that did not report their units or had units that were not the imperial or metric units of R/USLE. The problem of unclear or inconsistent units causes problems for future researchers in terms of adapting the rainfall erosivity or soil erodibility equations for their own study sites. Since the original R/USLE was formulated with US customary units, researchers must be careful to use the correct units and conversions to metric (Renard & Freimund, 1994). To convert from imperial to metric units, Renard et al. (1997) recommends a conversion factor of 17.02 for R-factor and 0.1317 for K-factor.

Summary and conclusion

This paper reviews the different components of the Universal Soil Loss Equation (USLE) and its updated form, the Revised Universal Soil Loss Equation (RUSLE). Different studies around the world were collected and analysed to compile how they adapted R/USLE to their unique conditions, how they had calculated rainfall erosivity with only the data available in their study site, and how these methods have been used by subsequent soil erosion studies. This paper presented some of the limitations of the R/USLE and outlined a few future directions: incorporating soil loss from other types of soil erosion, importance of estimating soil loss at sub-annual scales and recommended equations, and consistency in reporting units in future literature. At first glance, the USLE and its family of models seems like a relatively straightforward linear model. However, this review shows the difficulty in finding the most appropriate method of calculating its factors depending on location, availability of data, and previous studies done in nearby or similar regions. It is important for future researchers to consider which equations they adapt to their study area, and consider testing multiple methods of calculating one factor to see how the results affect soil loss estimates. The main purpose of this paper was to provide a reference point for future soil researchers by compiling equations for the R/USLE factors, references for C-factors and P-factors, and finding previous studies that may be relevant to their own work for their further investigation and literature review. In the end, the choices made regarding applications of the R/USLE depend on the kind of data that is available for a study area, and how they can adapt or change information from other studies to suit their area's particular climate, soil type, topography, typical land cover, and support practices.

Table A1. Summary of previous studies that have applied the USLE and RUSLE

Author	Location	R-factor	K-factor	LS-factor	C-factor	P-factor
David (1988)	Various watersheds in the Philippines	Mihara (1951) and Hudson (1971) as cited in David (1988)	Wischmeier and Mannering (1969)	Madarcos (1985) and Smith & Whitt (1947)	Literature	Literature
Eiumnoh (2000)	Sakae Krang watershed (Thailand)	El-Swaify et al. (1987) as cited in Merritt et al. (2004)	USLE method	USLE method	Literature	None observed (P=1)
Fernandez et al. (2003)	Lawyers Creek Watershed (USA)	USDA-ARS (2002)	From the SSURGO database (USDA)	Upslope contributing area method	Database from RUSLE software	Database from RUSLE software
Merritt et al. (2004)	Mae Chem watershed (Thailand)	El-Swaify et al. (1987) as cited in Merritt et al.	Previous studies in area	USLE method	Previous studies in area	Previous studies in area

		(2004)				
Post and Hartcher (2005)	Mae Chem watershed (Thailand)	El-Swaify et al. (1987) as cited in Merritt et al. (2004)	Previous studies in area	L = 1 S = derived from DEM	Previous studies in area	None observed (P=1)
Dumas and Fossey (2009)	Efate Island (Vanuatu)	Roose (1975) and Morgan (1994) as cited in Morgan (2005)	USLE method	RUSLE method at pixel level	Literature	None observed (P=1)
Adornado et al. (2009)	REINA (Philippines)	El-Swaify et al. (1987) as cited in Merritt et al. (2004)	Table by Stewart et al. (1975)	Upslope contributing area method	Literature	None observed (P=1)
Schmitt (2009)	Negros Island (Philippines)	RUSLE method	USLE method	RUSLE method at pixel level	Literature	Previous studies
Jayasinghe et al. (2010)	Nuwaraeliya (Sri Lanka)	El-Swaify et al. (1987) as cited in Merritt et al. (2004)	Table by Stewart et al. (1975)	Upslope contributing area method	Literature	None observed (P=1)
Jain and Das (2010)	Jharkhand (India)	Ram et al. (2004), as cited in Jain and Das (2010)	USLE method and previous studies	Upslope contributing area method	Literature	None observed (P=1)
Adornado and Yoshida (2010)	Bukidnon (Philippines) and also REINA (Philippines)	El-Swaify et al. (1987) as cited in Merritt et al. (2004)	Table by Stewart et al. (1975)	Upslope contributing area method	Literature	None observed (P=1)
Boyle et al. (2011)	California (USA)	From previous studies	From previous studies	Upslope contributing area method	Literature	N/A
Chen et al. (2011)	Xiangxi watershed (China)	Wischmeier and Smith (1978)	Williams and Renard (1983) nomograph	Upslope contributing area method	Using NDVI	N/A
Demirci & Karaburun (2012)	Buyukcekmece Lake watershed (Turkey)	Arnoldus (1980)	Torri et al. (1997) equation	Upslope contributing area method	Using NDVI	None observed (P=1)
Nontananandh and Changnoi (2012)	Songkhran watershed (Thailand)	Land Development Department (2000)	Values from Land Development Department (2000)	Modified RUSLE method	Literature	None observed (P=1)
Ozsoy et al. (2012)	Mustafakemalpasa River Basin (Turkey)	From previous studies	USLE method	RUSLE method, using a 3rd party programme	Literature	None observed (P=1)
Delgado & Canters (2012)	Claveria (Philippines)	Shamshad et al. (2008)	USLE method	RUSLE2 programme, using the upslope contributing area method	Literature	David (1989)
Hernandez et al. (2012) (used SedNet, which has an USLE	Pagsanjan (Philippines)	El-Swaify et al. (1987) as cited in Merritt et al. (2004)	Wischmeier and Mannering (1969)	Algorithm within SedNet	Literature	N/A

component)						
Sinha & Joshi (2012)	Maharashtra (India)	Roose (1975)	USLE method	Morgan (1986)	Literature	Literature
Nigel & Rughooputh (2012)	Mauritius	Arnoldus (1980), as cited in Le Roux et al. (2005)	From previous studies	Upslope contributing area method	Literature	Literature
Životić et al. (2012)	Nisava river basin (Serbia)	Wischmeier and Smith (1978)	USLE method	RUSLE method	Using NDVI	None observed (P=1)
Rozos et al. (2013)	Euboea Island (Greece)	Flabouris (2008)	Based on geological characteristics	Morgan (1986)	Literature	None observed (P=1)
Bagherzadeh (2014)	Masshad plain (Iran)	Wischmeier and Smith (1978)	USLE method	USLE method		None observed (P=1)
Ferreira and Panagopoulos (2014)	Alqueva (Portugal)	Similar to Loureiro and Coutinho (2001)	USLE method	Upslope contributing area method	Using NDVI	None observed (P=1)
Li et al. (2014)	Guangdong (China)	Zhou et al. (1995)	USLE method	Similar to RUSLE method	Using NDVI	1 for wasteland and built-up 0.5 for forested 0.2 for orchard land 0.35 for cropland
Zakerinejad and Maerker (2015) (used USPED, which has USLE components)	Mazayjan (Iran)	Ferro et al. (1991); Renard & Freimund (1994); Sadeghifard et al. (2004)	RUSLE method	Algorithm within USPED	Literature	None observed (P=1)
Jahun et al. (2015)	Crete (Greece)	Fu et al. (2006)	RUSLE method	Upslope contributing area method	Using NDVI	Previous studies
Farhan and Nawaiseh (2015)	Wadi Kerak catchment (Jordan)	Eltaif et al. (2010)	Similar to USLE nomograph	Upslope contributing area method	Literature	Literature
Panagos et al. (2015e) and related papers	Europe	Rainfall Intensity Summarisation Tool (RIST)	USLE method	3rd party programme	Literature	Literature
Russo (2015)	Brunei Darussalam	Rosewell & Turner (1992)	Rosewell (1997)	RUSLE method	Based on ground covered	None observed (P=1)
Nakil and Khire (2016)	Gangapur (India)	Nakil (2014)	USLE method	RUSLE method	Literature	Literature
Raissouni et al. (2016)	Smir Dam (Morocco)	Similar to Arnoldus (1980) methods	Merzouk (1985)	Upslope contributing area method	Literature	None observed (P=1)
Fernandez and Daigneault (2016)	Waikato (New Zealand)	Institute of Water Research (2015)	Dymond et al. (2010)	Upslope contributing area method	Range between 1 (wood vegetation) and 10 (herbaceous	

					vegetation or bare ground)	
Duarte et al. (2016)	Montalegre (Portugal)	Loureiro and Coutinho (2001)	USLE method	USLE method	Literature	Literature
Gaubi et al. (2017)	Lebna watershed (Tunisia)	Rango and Arnoldus (1987)	USLE method	Upslope contributing area method	Literature	None observed (P=1)

Acknowledgements

The work presented in this paper is supported by the Victoria University of Wellington Doctoral Scholarship as part of the PhD research of R. Benavidez. This manuscript benefited from the input of Dr. Kevin Norton, senior lecturer at the School of Geography, Environment and Earth Sciences at Victoria University of Wellington.

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