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Assessing the applicability of the Revised Universal Soil Loss Equation (RUSLE) to Irish Catchments

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Abstract Elevated suspended sediment concentrations in fluvial environments have important implications for system ecology and even small concentrations may have serious consequences for sensitive ecosystems or organisms, such as freshwater pearl mussels (*Margaritifera margaritifera*). Informed decision making is therefore required for land managers to understand and control soil erosion and sediment delivery to the river network. However, given that monitoring of sediment fluxes requires financial and human resources which are often limited at a national scale, sediment mobilisation and delivery models are commonly used for sediment yield estimation and management. The Revised Universal Soil Loss Equation (RUSLE) is the most widely used model for overland flow erosion and can, when combined with a sediment delivery ratio (SDR), provide reasonable sediment load estimations for a catchment. This paper presents RUSLE factors established from extant GIS and rainfall datasets that are incorporated into a flexible catchment modelling approach. We believe that this is the first time that results from a RUSLE application at a national scale are tested against measured sediment yield values available from Ireland. An initial assessment of RUSLE applied to Irish conditions indicates an overestimation of modelled sediment yield values for most of the selected catchments. Improved methods for model and SDR factors estimation are needed to account for Irish conditions and catchment characteristics. Nonetheless, validation and testing of the model in this study using observed values is an important step towards more effective sediment yield modelling tools for nationwide applications.

Key words Ireland; soil loss modelling; RUSLE; sediment yield; validation

INTRODUCTION

Fine sediments are of particular interest for catchment management, because excessive concentrations can have detrimental impacts on freshwater biota. When suspended within the water column, sediments reduce light penetration affecting primary and higher trophic level production and can adversely affect fish populations by causing elevated levels of stress and physical damage to organs, as well as reducing dissolved oxygen levels and water quality (Kemp *et al.* 2011). Fine sediments also play an important role in the transfer of nutrients, heavy metals and other pollutants (e.g. Owens *et al.* 2001), through sorption processes to fine grained sediments (typically <63 μm). When deposited, sediments can adversely affect the richness and density of macroinvertebrate communities (Jones *et al.* 2012), and siltation into coarse gravels and the crucial Hyporheic Zone (Lawler *et al.* 2009) may result in local deoxygenation and consequently degradation of important habitats such as fish spawning grounds (e.g. Heywood & Walling, 2007) and freshwater pearl mussel (*Margaritifera margaritifera*) beds.

The European Water Framework Directive (WFD) (2000/60/EC) does not currently provide adequate guidelines for standards of suspended or deposited sediments. The annual average suspended sediment concentration (SSC) limit of 25 mg L^{-1} under the EU Freshwater Fish Directive (2006/44/EC) does not consider high temporal and spatial variations of sediment transport across a range of catchment characteristics (e.g. Lawler *et al.* 2006), or consider complex and variable biological response to fine sediments in fluvial systems (Bilotta & Brazier, 2008; Collins *et al.* 2011; Kemp *et al.* 2011).

Sediment flux data are limited to a few studies for Ireland, showing sediment yields of between 0.03–0.44 tonnes ha^{-1} $year^{-1}$ (Table 1). Although these values are low compared to those reported for other European countries (Vanmaercke *et al.* 2011), SSC levels as high as 117 mg L^{-1} and 590 mg L^{-1} have been recorded during flood periods (Harrington & Harrington, 2013) and values above the 25 mg L^{-1} guideline have been reported in Irish catchments, including periods of potential salmon migration and spawning (Thompson *et al.* 2014). Given the presence of siltation-sensitive habitats, including Atlantic salmon spawning grounds and freshwater pearl mussel beds (NPWS, 2008), Ireland faces a challenge to set new guidelines for sediment regimes and limits. This requires high resolution monitoring of suspended and deposited sediment loading that must link to impacts on the ecology of freshwater biota. Although research is currently underway in Ireland under academic institutions and state agencies such as the Environmental Protection Agency (EPA), Teagasc, Marine Institute, Office of Public Work (OPW), logistic and economic constraints mean that these investigations are limited to a low number of catchments. Empirical sediment data may therefore be insufficient for decision-making purposes and complementary support tools, such as sediment mobilisation and delivery models will be necessary for more appropriate sediment yield estimation at the national scale.

Table 1 Suspended sediment yield data in Ireland.

Catchment	Area (km^2)	Sediment yield* (tonnes ha^{-1} $year^{-1}$)	Study period	Reference
Mount Stewart	7.52	0.067	Sept 2011-Sept 2012	Thompson *et al.* 2014
Dunleer	9.4	0.15	Oct 2009-Sept 2010	Melland *et al.* 2010
	9.4	0.135	Oct 2010-Sept 2011	Melland *et al.* 2010
Castledockrell	11	0.177	Oct 2009-Sept 2010	Melland *et al.* 2010
	11	0.031	Oct 2010-Sept 2011	Melland *et al.* 2010
Dripsey	15.24	0.161	Jan 2002-Dec 2002	Kiely *et al.* 2007
	15.24	0.098	Jan 2003-Dec 2003	Kiely *et al.* 2007
Glenamong	17.91	0.16	2001	May *et al.* 2005
Mattock	20.96	0.44	Nov 2011-Nov 2012	Thompson *et al.* 2014
Clarianna	29.8	0.085	Jan 2002-Dec 2002	Kiely *et al.* 2007
The Oona	84.5	0.29	Oct 2000-Sept 2002	Kiely *et al.* 2007
	84.5	0.41	Jan 2002-Dec 2002	Kiely *et al.* 2007
Owenabue	103	0.256	Sept 2009-Sept 2010	Harrington & Harrington 2013
Bandon	424	0.142	Feb 2010-Feb 2011	Harrington & Harrington 2013

*When sediment flux was reported in the study it was converted into sediment yield units by dividing flux values by catchment size. Other units like kg ha^{-1} $year^{-1}$ or tonnes km^{-2} $year^{-1}$ were also converted to uniform units of tonnes ha^{-1} $year^{-1}$.

The Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) and the more recent Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.* 1997) are widely used to model erosion by overland flow. Although these models were originally designed to estimate soil loss on a field-plot scale, they can be combined with the concept of the sediment delivery ratio (SDR) (Walling, 1983) to provide sediment load estimation at a catchment scale, although not without problems (e.g. Parsons *et al.* 2008; Kinnell 2010). Many non-point source pollution catchment-scale models base overland sediment transport modelling on the USLE and its variations (Borah & Bera, 2003), mainly due to its simplicity in application. In Ireland, the USLE was previously applied to the small Burrishoole catchment using empirical data for a sub-catchment (the Glenamong) to calibrate the model (May & Place 2005). The RUSLE has also been applied at the national scale to estimate soil erosion and, combined with a Sediment Delivery Distributed (SEDD) model, was used to estimate sediment yield for the Mallow catchment (He, 2010). The nationwide application of RUSLE, however, has thus far lacked validation against measured data that would better confirm its suitability for Irish conditions.

This study aims to investigate the applicability of the RUSLE to Irish catchments and to assess its utility as a national sediment yield assessment tool. The study provides a comparison of modelled sediment yield values to those observed in selected Irish catchments (Fig. 1), which represents an important new step towards assessing the wider application of RUSLE in Ireland.

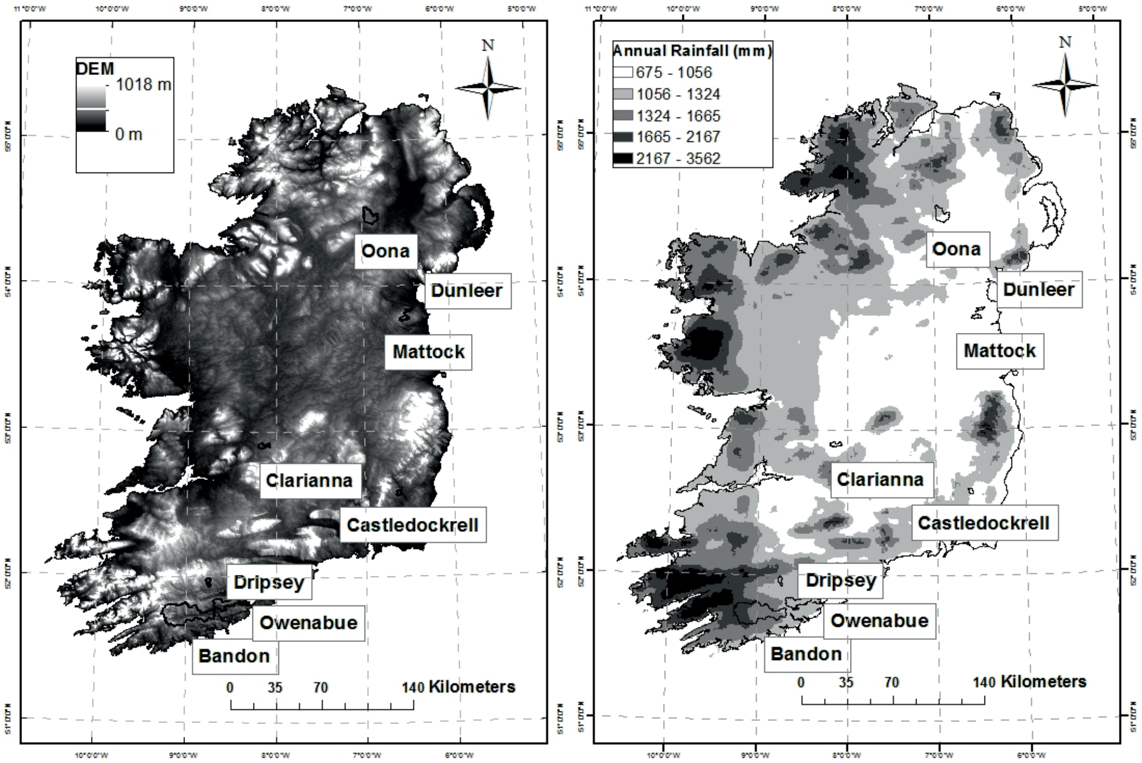

Fig. 1 Study catchments and corresponding topography and average annual precipitation pattern (data sources: EPA and Met Éireann). Note that both average annual precipitation, and rainfall seasonality, increases from east to west across Ireland (Walsh & Lawler, 1981).

MATERIALS AND METHODS

RUSLE and SDR were applied to eight Irish catchments and compared to 12 measured annual sediment yield values. Study catchments were delineated using digital elevation model (DEM) datasets based on the information provided in the corresponding studies, and RUSLE factors were derived from available rainfall data and GIS datasets.

RUSLE estimates mean annual soil loss (SL) according to:

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{1}$$

where A = mean annual soil loss (tonnes ha^{-1} year^{-1}), R = the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}), K = the soil erodibility factor (tonnes h MJ^{-1} mm^{-1}), LS = the topographic factor (dimensionless), C = the crop management factor (dimensionless), P = the erosion control practice factor (dimensionless). The details of the factors and how they are estimated are discussed in Renard *et al.* (1997), and an example of the approach is provided in Ranzi *et al.* (2012).

Rainfall erosivity factor (*R*)

Data with one hour, 30 minute, 15 minute and 1 minute resolution at the nearest meteorological station to the study catchment were used to calculate the individual annual *R* factor specific to the corresponding study period (data source: Met Éireann, http://www.met.ie/). Rainfall data were converted to 10 min intervals and the *R* factor was calculated based on storm EI_{30} values (product of storm kinetic energy and the maximum 30-min intensity), using the algorithm implemented in C programming language available from the European Soil Portal – Soil Data Information System (Meusburger *et al.* 2012; Panagos *et al.* 2012).

Calculations were only performed on potentially significant erosive events, using criteria provided by Renard *et al.* (1997), where storms of at least 12.7 mm total precipitation, or smaller storms with at least 6.35 mm rain falling in 15 min, were considered. Precipitation of less than 1.27 mm over 6 hours was used to divide a longer storm into two individual storms.

Soil erodibility factor (*K*)

To estimate the *K* factor, a soil erodibility GIS map at 500-m resolution was used. This was prepared with the Land Use/Cover Area frame Survey (LUCAS) soil survey data available for 25 Member States of the European Union (Panagos *et al.* 2014).

Slope length and steepness factor (*LS*)

Taking into consideration the complexity of algorithms for quantifying the *LS* factor and the need for the ease of application for a national scale modelling tool, it was proposed to simplify the estimation of this factor and link it to the national DEM and sub-basins drainage density characteristics by relating the steepness of the catchment to the distance to the nearest stream.

The proposed *LS* factor is calculated as:

$$LS = S / drainD \tag{2}$$

where S = the average gradient of the slope (degrees) and $drainD$ = the drainage density factor, calculated for each sub-basin as:

$$drainD = strLength / area \tag{3}$$

where $strLength$ = length of stream network (km), $area$ = area of sub-basin (km^2).

The *LS* factor was calculated for each study catchment using equation (2) and compared to average *LS* value estimated for each catchment using the upslope contributing area (UCA) method, described by Mitasova *et al.*(1996) and Mitasova *et al.*(2010 [online]), thus:

$$LS = (m+1) \cdot \left[UCA / a_0\right]^m \cdot \left[\sin b / b_0\right]^n \tag{4}$$

where UCA is upslope contributing area per unit contour width, b [degrees] is the slope angle, m = 0.4–0.6, n =1.0–1.4, a_0 = is the length of 22.1 m, b_0 = is the slope of the standard USLE plot at 0.09 or 9%. In this study values of m = 0.6 and n = 1.3 were used (Moore & Wilson 1992). Equation (4) incorporated into the GIS Raster Calculator tool is expressed as:

$$Power((flow\_acc \cdot cell\_res)/22.13,0.6) \cdot Power(\sin(slope \cdot 0.01745)/0.09,1.3) \cdot 1.6 \tag{5}$$

This method requires a flow accumulation (*flow_acc*) grid which can be derived from a DEM, and in this study it was derived and obtained from national EPA datasets at 20 m resolution.

Vegetation cover and crop management factor (*C*)

The *C* factor values were assigned to each land use class for the CORINE 2006 land cover GIS map, based on values found in the literature. The *C* factor for all arable areas was set to a long-term average value of 0.3, pasture areas to 0.01 and forest to 0.001. These values have been most widely employed in other studies (e.g. Bakker *et al.* 2008). Peat land was assigned a value of 0.56, which has been previously used for wetland land use in the global soil erosion estimate study (Pham *et al.* 2001).

Support practice factor (*P*)

As there is no significant support practice for arable land in Ireland (and information on subsurface drainage is not available) this factor is assumed to be equal to 1 for Irish catchments.

Sediment delivery ratio (*SDR*)

In this study a simple relation (based on studies from 300 watersheds throughout the world) between catchment size and SDR by Vanoni (1975) was chosen:

$$SDR = 0.42 CA^{-0.125} \tag{6}$$

where CA = catchment drainage area in square miles.

RESULTS AND DISCUSSION

Average RUSLE factor values and modelled annual sediment yields for study catchments are presented in Tables 2 and 3, respectively. Results show an overestimated sediment yield assessment for five catchments (Dunleer, Castledockrell, Dripsey, Owenabue and Bandon), whereas predicted values for the Oona and Mattock rivers are about 50% lower than the observed values. The Clarianna sediment yield modelled with the LS_2 factor (using topographic factor calculated with equation (4), see Table 2) produced a close correspondence to the measured value.

The biggest percentage differences between modelled and observed sediment yield values were found in two small catchments, namely the Dripsey and Castledockrell. These high values are mainly the result of a high R factor (Dripsey) and high LS factor (Castledockrell). Slightly smaller overestimation of sediment yield found in the Bandon and Owenabue catchments can be attributed to the relatively large catchment areas. Subdividing these catchments into sub-basin scales may decrease high values of LS found in these catchments and consequently improve sediment yield prediction.

Table 2 Estimates of mean RUSLE factors and SDR for Irish catchments.

Catchment	R	K	LS_1	LS_2	C	SDR
Dunleer (year 1)	143.5	0.0301	1.72	2.54	0.1355	0.36
Dunleer (year 2)	116	0.0301	1.72	2.54	0.1355	0.36
Castledockrell (year 1)	364.6	0.0313	3.06	4.08	0.2119	0.35
Castledockrell (year 2)	96.2	0.0313	3.06	4.08	0.2119	0.35
Dripsey (year 1)	726.3	0.0290	3.15	2.83	0.1140	0.34
Dripsey (year 2)	410.9	0.0290	3.15	2.83	0.1140	0.34
Mattock	138	0.0273	3.41	3.87	0.0417	0.32
Clarianna	107.3	0.0268	2.84	1.18	0.0782	0.31
The Oona (year 1)	121.4	0.0238	3.49	-	0.0471	0.27
The Oona (year 2)	182.7	0.0238	3.49	-	0.0471	0.27
Owenabue	378.3	0.0301	3.85	4.4	0.1002	0.27
Bandon	295.1	0.0279	4.22	3.31	0.0857	0.22

R – Rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}), K – Soil erodibility (tonnes h MJ^{-1} mm^{-1}),
LS_1 – topographic factor calculated with equation (2), LS_2 – topographic factor calculated with equation (4),
C – the crop management factor, SDR – sediment delivery ratio

Table 3 Estimates of modelled soil loss and sediment yield for Irish catchments.

Catchment	SL_1	SL_2	SY_{m1}	% diff	SY_{m2}	% diff	SY_{obs}
Dunleer (year 1)	1.01	1.49	0.362	+142	0.535	+257	0.15
Dunleer (year 2)	0.81	1.20	0.293	+117	0.433	+220	0.135
Castledockrell (year 1)	7.40	9.87	2.590	+1363	3.453	+1851	0.177
Castledockrell (year 2)	1.95	2.60	0.683	+2104	0.911	+2839	0.031
Dripsey (year 1)	7.56	6.80	2.572	+1497	2.310	+1335	0.161
Dripsey (year 2)	4.28	3.84	1.455	+1385	1.307	+1234	0.098
Mattock	0.54	0.61	**0.173**	–61	**0.196**	–55	0.44
Clarianna	0.64	0.27	0.198	+133	**0.082**	–3	0.085
The Oona (year 1)	0.47	-	**0.128**	–56	-	-	0.29
The Oona (year 2)	0.71	-	**0.193**	–53	-	-	0.41
Owenabue	4.39	5.02	1.186	+ 363	1.355	+429	0.256
Bandon	2.98	2.34	0.655	+ 352	0.514	+255	0.142

SL – average soil loss (tonnes ha^{-1} year^{-}1), SY_m – modelled sediment yield estimated (tonnes ha^{-1} year^{-1})
(Note: suffix 1 = values estimated with LS_1, suffix 2 = values estimated with LS_2, SY_{obs} – observed sediment yield (tonnes ha^{-1} year^{-1}), % diff = percentage difference between modelled and observed values;
Bold values indicate positive estimates of sediment yield in comparison to the observed values

Model uncertainties

The *R* factor is the only element in RUSLE that can differentiate between different measured values for dry and wet years (since no major land-use change was recorded). Percentage change in calculated *R* factors between years one and two corresponds well to a percentage change in measured sediment yields between these years. Thus, it can be concluded that calculated *R* factors represent the erosive nature of events reasonably well. However, some uncertainty is introduced when data for the nearest synoptic station (with high resolution record) is used as opposed to original data for the catchment.

The soil erodibility factor has to be further validated against national soil datasets. The crop cover factor can also be improved by considering different values for pastures depending on livestock densities and increased values for winter crops.

Comparison of *LS* factors calculated with the two methods indicates potential for the use of catchment descriptors in the estimation of this factor. Further improvement of the slope-drainage density method may include different slope classes instead of lumped mean values. Moreover, the small percentage of very high cell grid values in the GIS LS_2 raster maps resulted in high standard deviation values (7.84–123.4 between study catchments), which may indicate that the average value does not represent this factor fully. Calculation of this factor needs to be investigated further with the possibility of including different methods for LS estimation.

Although SDR estimated with the drainage area method is convenient to use, adaptation of this method at a small sub-basin scale will assume a delivery ratio of about 35%, which may be overestimating sediment transfer from the catchments. A different approach incorporating other catchment characteristics needs to be investigated for further improvement of this factor.

Finally, it should be noted that the RUSLE model only predicts surface soil erosion and does not takes into account channel bank erosion, which can be a very important sediment source in both lowland and upland catchments (e.g. Lawler, 2008). Walling (2005) reported a 5–48% contribution of channel bank erosion to sediment yields for 34 UK catchments, and contributions as high as 66–89% were reported in the Gelbæk catchment in Denmark (Kronvang *et al.* 1997). Underestimated sediment yield values in this study may therefore be improved with the inclusion of a bank erosion factor, although this would exacerbate the already overestimated values that were observed in the majority of modelled sediment yields.

CONCLUSIONS

Models can be used to identify areas with a relatively high risk of contributing sediment pollution to rivers. Catchment scientists can use this information to understand sediment generation and delivery processes, target mitigation measures and enforce agricultural policies. This study assesses the suitability of RUSLE and SDR for predicting high risk areas for sediment mobilisation and delivery at the basin scale.

A comparison of the RUSLE model with observed values contributes to a better understanding of the mechanisms leading to catchment soil loss and also constitutes an important step towards the construction of a national sediment assessment tool. The methods for determining RUSLE factors are under review as the model is currently overestimating sediment yield in most catchments. The slope-drainage density method for the *LS* factor estimation shows promising results, and although this approach overestimates sediment yield for some catchments, it does provide a better estimation for some of the catchments than the UCA method.

A very good model fit for Clarianna catchment and positive results for the Oona and Mattock indicate the potential of the RUSLE model as an assessment tool. However, further work is required to improve the RUSLE factor estimations and appropriate SDR measures for Irish conditions.

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