Environment and Rural Affairs Monitoring & Modelling Programme

ERAMMP Year 1 Report 18: Technologies to Capture Evidence of Soil Erosion

New and existing technologies that can to be used for capturing evidence on the extent of soil erosion (with a particular emphasis on monitoring of landslips, peatland and bankside erosion)

Tye, A.[1] & Robinson, D.A.[2]

[1] British Geological Survey, [2] Centre for Ecology & Hydrology

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CEH contact details	Bronwen Williams Centre for Ecology & Hydrology, Environment Centre Wales, Deiniol Road, Bangor, Gwynedd, LL57 2UW t: 01248 374500 e: erammp@ceh.ac.uk
Corresponding Author	David Robinson, CEH
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Contents

Abbreviations and some of the technical terms used in this report are expanded in the project glossary: https://erammp.wales/en/glossary (English) and https://erammp.cymru/geirfa (Welsh)

1 Introduction

Soil erosion is considered one of the greatest threats to food supply across the globe as outlined in the FAO report ‘Status of the World’s Soil Resources’ (FAO, 2015). Issues regarding soil erosion have been compounded because, whilst erosion effects are evident, little is known about the soil formation rates. However, it is generally accepted that the rate of soil erosion under conventional cultivation tends to be at least one to two orders of magnitude greater than soil formation (Montgomery et al. 2007). Thus it is apparent that within any monitoring and land use planning programme, soil erosion is a key parameter that needs to be considered. The effects of soil erosion often extend beyond the field and can contribute to the eutrophication of waters, poor water quality leading to poor ecosystem function and sedimentation of water courses.

When considering soil erosion and its monitoring, it is not only important to understand the principal processes through which water (sheet, rill and gully erosion) and wind (saltation) erode soil, but also the many additional factors which influence the rates of soil erosion. These include properties such as soil texture, slope angle and slope length that can be measured and remain for all purposes static variables, along with those factors that which are largely unpredictable, such as the timing and intensity of storms in relation to vegetation coverage. Two assessments of the extent of soils under unacceptable potential threat of erosion in England and Wales are shown in Figure 1, based on soil characteristics.

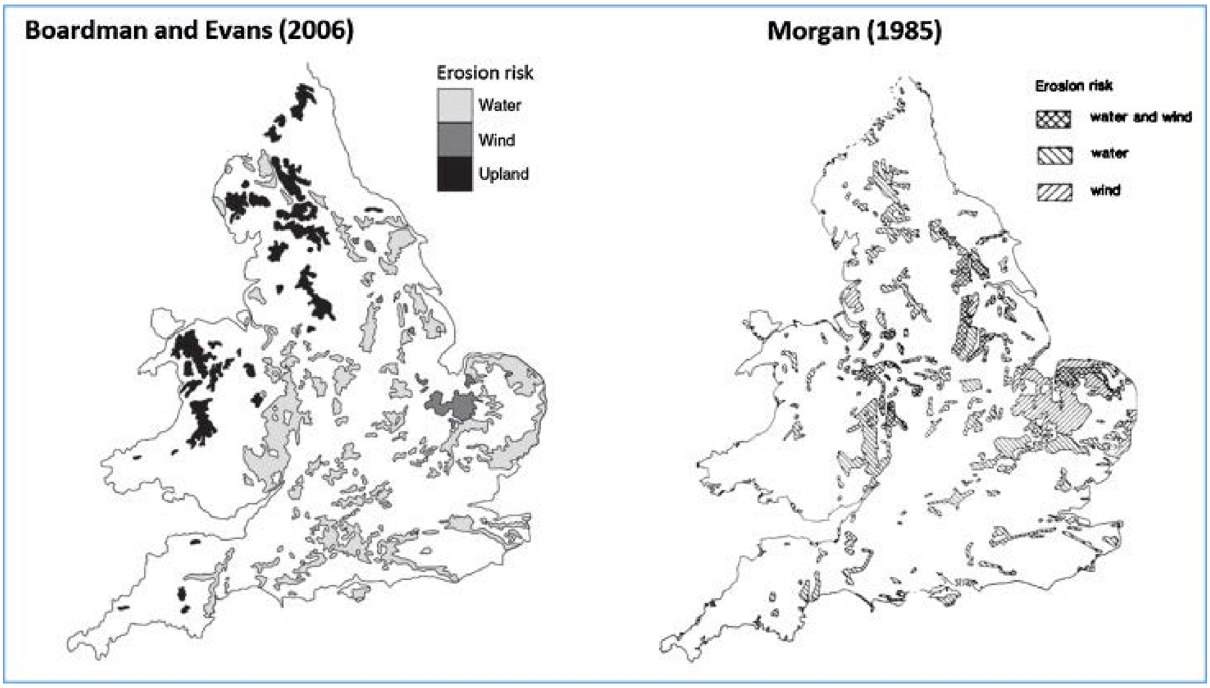

Figure 1: Two assessments of the erodibility of soils in England and Wales with associated erosion risk.

As a result of the variables contributing to soil erosion, a large number of techniques have been developed to quantify soil loss and act as a basis for developing mitigation techniques. These techniques operate over a range of different spatial scales, extending from plot to field to catchment to national scale and over a range of temporal scales from single event to decadal. This is in part a reflection on the different erosion processes and their potential magnitude. For example, rill and gully erosion may be fairly local but they can produce significant soil erosion (see Figure 1) whereas sheet wash erosion on slopes can be widespread but the erosion rate may only typically be between 0.1 -0.3 t ha yr^{-1} (Evans et al. 2017). In addition to selecting appropriate techniques, methodological uncertainties exist, such as the continued debate involving the use of ^{137}Cs (radiocaesium - a radioactive isotope of caesium) as a measure of soil redistribution across fields (Parsons and Foster, 2011).

Before discussing the different available methodologies there are major overarching questions which need to be addressed when designing a monitoring process. These are:

1. ***What questions are to be answered with the monitoring survey?***

- Is knowing the rate of net or gross soil erosion from or within fields more important than understanding and identifying the thresholds and drivers in the spatial area where soil erosion is occurring so that wider considerations to soil conservation and mitigation of erosion can be made across Wales?
- Over what time scale are assessments to be made?

2. ***Can the monitoring survey be developed to account for new drivers?***

- Can the techniques selected account for erosion in both arable and grassland soils where the processes are likely to be driven by very different processes (e.g. poaching, compaction, bank erosion in grassland; tramlines in arable)
- Will the monitoring survey be able to account for changes caused in widespread agricultural practice (e.g. greater maize growth) or changes in land-use caused by changes in government support for the farming industry?

3. ***Should a combination of approaches be considered as not all methods of soil erosion measurement are appropriate at all scales?***

2 The task requirements

- Assess the range of techniques available to measure soil erosion and describe the scale over which they may operate along with their major advantages and disadvantages (Section 2.1).
- Provide some estimates of costs associated with selected methods (Section 2.2).
- Identify the extent that new technologies can be used within a soil erosion monitoring programme (Section 2.3).

2.1 Table of erosion methodologies

A review of current methodologies used in soil erosion studies can be found in Table 1. These are split up into a series of categories including (i) Process Understanding, (ii) Direct measurement / Assessment, (iii) Indirect Measurement, (iv) Remote Sensing Technologies and (v) Prediction. Table 1 illustrates the complexity of soil erosion assessment and the range of different scales that can be measured, along with the importance of selecting the right technique for the land use and temporal period. In Wales, the techniques should be ideally suitable for both grassland and arable agriculture. Riverbank erosion is also another important erosional feature which often is overlooked. The temporal scale is important. For example, the use of ^{137}Cs provides a measure of erosion that is an average over ~50 years (since bomb and Chernobyl deposition), and therefore avoids major events that happen very occasionally and those years when erosion may not take place (or is minimal). It also, when used on arable land, includes the contribution of tillage erosion which could be the dominant process.

A further consideration when choosing techniques is how to account for eroded soil stored within the landscape. This again is a question of methodology and how erosion rates are measured and averaged. Thus, in many cases erosion only occurs in a small part of the landscape, and often the soil is stored within that landscape (i.e. it doesn’t reach a water course because there is no hydraulic connectivity). Therefore catchment scale measurements using turbidity sensors only provide an estimate of net erosion that has made its way to the hydrological system. It is common that as the catchment size increases, net erosion per unit area decreases because of the reduction in hydrological connectivity to water courses.

Table 1: Methods of measuring soil erosion

Method		Scale	Time scale	Description of method	Method advantages	Method limitations	References
Process Understanding	Soil Plots.	Slope length.	From Daily (event based).	Measurements normally taken on purpose built plots with soil collection facilities.	Can test different slope lengths, textures, rainfall intensities to assess their influence on erosion processes.	Edge effects of plots may not fully represent field conditions.	e.g. Fullen 1991
	Rare Earth Metals.	Field / slope length.	Single events to longer periods.	Rare earth metals mixed in with soil at enhanced concentrations.	Strong adsorption to soil particles. Sensitivity to analysis- low background concentrations. No interference with transport processes. Low plant uptake. Environmentally safe.	Assumption is that PSD of source and sediment are similar - may not be suitable for sandy soils. Size selectivity occurs on steep slopes.	e.g. Kimoto et al. 2006 Gang Liu et al. 2016
	Rainfall Simulators.	Laboratory			Can test different slope lengths, textures, rainfall intensities. Designed to look at process.	May not be an accurate representation of field conditions.	
Direct Measurement / Assessment	^{137}Cs	Field / slope length.	Normally once – Few if any studies have undertaken repeat measurements.	^{137}Cs behaves similarly to K^+ and is bound to soil particles. Soil cores are collected and split into depth increments. Gamma spectrometry used for analysis. Models used to define redistribution. Can be used for wind erosion as well.	Works on the principal of redistribution across fields and slopes and incorporates rill, gully, wind and tillage erosion in one measurement. Therefore is ideal for arable land. Has been used in agricultural and semi/natural ecosystems. Gamma counting equipment provides relatively cheap analysis, although time consuming. Can be used to indicate where erosion and deposition is occurring through a number of processes. Examines changes of ^{137}Cs with depth (normally to 30cm).	Finding Reference sites close by which have received the same amount of ^{137}Cs deposition as field sites is often challenging – the practice of high replication numbers for background ^{137}Cs status need to be adopted. Variable bomb and Chernobyl fallout produces problems with reference sites. The calculation of actual erosion rates have been fiercely debated in recent years – its use on arable land and the effects of tillage erosion will therefore over-estimate water erosion rates. Therefore using ^{137}Cs rates to predict purely water	e.g. Defra Research Report SP0411 (2005); Walling and Quine (1991) Quine and Walling (1991);

Method		Scale	Time scale	Description of method	Method advantages	Method limitations	References
						erosion on arable sites should be avoided. Temporal average only (usually over 50 years – not suitable for individual events. Decay rate of Cs means that with time error associated with measurements will increase. Cs acts in a similar manner to K and can be taken up by plants.	
	Erosion Pins		Would require reasonable redistribution to occur to be measured – monthly - yearly.	Arrays of pins can be set up.	Provide simple and cheap method to provide change in surface height of soil (i.e. erosion and deposition) at specific points. Pin arrays can be set up rapidly. Excellent for natural / semi natural ecosystems.	Require good statistical design to develop point data to incorporate spatial extent Not useful for tillage erosion where redistribution of soil would negate effectiveness	
	Walk over / volumetric surveys	Field - catchment	Repeatable as often as required Often undertaken by identifying fields on a long transect	Surveys have been used to assess extent of rill and gully erosion Volumetric assessments of rill and gulley erosion can be made Sediment deposits such as wind-blown deposits and losses from field can also be logged.	Provides cheap, quick and repeatable assessments of yearly water erosion, particularly in arable fields. Has been regularly used (e.g. McHugh 2002; 2000). New hand based LIDAR scanners which don't need a base station can provide accurate volumetric analysis. Low staff knowledge – easily trained.	Cannot account for sheet or tillage erosion. Difficult to ensure all features are measured and mapped. Difficult to calculate the corresponding upslope contributing area to enable conversion to t ha yr^{-1}. Difficult to use on grassland as extent of erosion is often hidden. May take a lot of man hours to undertake extensive survey if volumetric measurements to take place.	McHugh 2007 McHugh et al. 2002 Evans 2002
	Ground based terrestrial LIDAR scanning.	Measuring long term erosion,	Can give highly accurate assessments of		New systems don't need a base station as they can automatically pick up satellite positioning so	Can be expensive to set up with systems costing ~£60+ K.	

Method		Scale	Time scale	Description of method	Method advantages	Method limitations	References
		and specific events (e.g. gulley erosion).	volumetric soil erosion.		increasing the flexibility and speed of scanning sites. Excellent for repeat measurements of river banks to assess their erosion.	Cannot always account for sheet or tillage erosion. Difficult to ensure all features are measured and mapped. Difficult to calculate the corresponding upslope contributing area to enable conversion to t ha yr^{-1}. Difficult to use on grassland as extent of erosion is often hidden.	
Indirect measurement	Turbidity Meters.	Catchment scale.	Hourly onwards.		Analogue of suspended sediment. Calibration curve required by setting up auto samplers to collect samples. Large datasets quickly and easily manipulated in 'R' or similar packages once code is written. Allows investigation of erosion processes linked to factors such as rain intensity, as well as the hysteresis of suspended sediment concentrations, in addition to annual fluxes. Able to monitor catchment erosion changes especially if land use, cultivation techniques change e.g. deforestation. Can be linked in to current HMS / EA installations.	Require good flow data to form ratings curve. Do not tell where erosion events within the catchment are occurring. Results demonstrate how the sediment delivery ratio is probably only a small proportion of catchment erosion (see point above). Costly equipment set up + additional costs for cleaning probes, downloading data etc. Will account for under-field drainage.	
	Reservoir / Pond Surveys.	Catchment scale.	Over period of time.		Reservoirs / ponds often need draining to be able to undertake.	Do not tell where erosion events within the catchment are occurring. Normally one off measurements to get historical record only.	e.g. Butcher et al. (1993), He et al. (1996),

Method		Scale	Time scale	Description of method	Method advantages	Method limitations	References
						There will be errors associated with the efficiency of sediment trapping and how much flows straight out of pond or reservoir.	Labadz et al. (1991), Rowan et al. (1995),
	Traditional suspended sediment surveys.	Catchment scale.	Over period of time.		Calibration curves required for rising and falling limbs.	Require good flow data to form ratings curve. Will account for under-field drainage.	Collins (1981) Heywood & Walling (2003), Walling & Amos (1999), Wass & Leeks (1999)
Remote Sensing Technologies	Satellite data. (E.g. Sentinel, Landsat, Worldview 3, Planetscope).	Large scale.	User defined but is also dependent on satellite flyover times.	Satellites use data from spectral bands. For example Landsat uses data from the visible (red, green, blue), reflective infra-red, middle infra-red and thermal infra-red of the electromagnetic spectrum. These bands are used to identify bare soil indices, vegetation indices using algorithms. Resolution ~10m for Sentinel and 30m for Landsat.	Good for identifying areas of erosion. Can be used in remote areas and to identify vegetation free surfaces. Image archives allow assessment of change with time. Most suited to investigating gully erosion but some studies have looked at sheet and rills through their spectral signatures. Fairly responsive to recent erosion events.	Spectral signatures can be limited by cloud cover. Calibrations required for developing time series. Fly over times limit capacity for rapid measurements of new erosion events. Would need to check whether resolution of image is of good enough quality for the type of erosion event to be monitored. Often time consuming data processing requiring skilled personnel. Costs of images can be expensive, particularly subscription services such as Planetscope. Still require considerable R & D to convert light images to measured soil erosion. Can only see bare soil, not when vegetation is present.	e.g. (Separu and Dube, 2018)

Method		Scale	Time scale	Description of method	Method advantages	Method limitations	References
	Airborne photography / LIDAR	Can be undertaken according to budget.		Resolution can be very high (e.g. 25cm).	Effective to monitor areas of erosion but volumes cannot be undertaken. Google blue-sky offers a platform but depends on up-dating of photographs. Possibility that archives exist so that temporal and spatial aspects of erosion can be examined. Excellent for repeat measurements of river banks to assess their erosion. Airborne photography can have a higher resolution than satellite.	Would need to check whether resolution of image is of good enough quality for the type of erosion event to be monitored. Not flown as often as satellites. Line of sight issues may arise in steep areas.	
	Structure from motion photogrammetry.	Field / landscape scale.	Repeatable as often as required.	Method uses UAV along with digital photography with the aim of creating DEM's in 3D from 2D imagery.	Highly suitable for upland or relatively inaccessible by foot areas. Low cost compared to Terrestrial LIDAR – Full kit can cost approx. £1000, GPS and camera systems. Pre-programmed flight paths can be used to ensure coverage of area. Results compare well with Terrestrial LIDAR. Suitable for erosion features e.g. rills and gulleys but not more general sheetwash. Can tackle areas in the hectares. Excellent for repeat measurements of river banks to assess their erosion.	Flights are weather dependent with wind speed being particularly critical. In upland areas where wind speeds are often higher the upper limit of 30 km hr^{-1} may be reached more often. Equipment heavier for transport than GBPS (see next line), which may limit access to remote sites.	
	Ground Based Photographic systems (GBPS).	Field / landscape scale.	Repeatable as often as required.	Method uses ground based photographs to be taken at oblique angles around erosion features, with geo referencing through	Highly suitable for upland or relatively inaccessible by foot areas. Low cost compared to Terrestrial LIDAR.	Only suitable for erosion features e.g. rills and gulleys and not more general sheetwash. More suitable for small areas (e.g. 0.1 ha).	

Method		Scale	Time scale	Description of method	Method advantages	Method limitations	References
				a number (20-30) ground control points.	– Full kit can cost approx. £1000 including airframe, autopilot, GPS and camera systems. Results compare well with Terrestrial LIDAR. Resolution can be as good as 2cm. Comparable results to TL (DEFRA SP1311). Can be used for repeat measurements of river banks to assess their erosion.		
Prediction	Computer modelling using models such as the Universal Soil loss equation (USLE) or Revised Universal Soil Loss equation.	Local to National scale.	Repeatable as often as required. With adjustments to input datasets for different scenarios.		Very useful in that they can be used to estimate the likely direction of change if a key erosion parameter (e.g. land use or climate) were to change over a range of spatial and temporal scales.	Likely to over-estimate actual erosion rates compared to volumetric measurements. Do not account for under-field drainage soil erosion. National Scale models already undertaken for England and Wales under DEFRA and GMEP projects.	e.g. Cooper et al. 2010
	Computer modelling using landscape models e.g. Caesar, CLYDE.	Catchment scale normally.	Long term landscape evolution models with soil erosion included.	Track sediment from landscape and through river system as sediment transport.	Reasonably effective at modelling long term rates.	Contain models such as RSULE so subject to errors within models. Do not account for under-field drainage soil erosion.	e.g. Tye et al. 2013
Landslides							
	Remote sensing technologies as described above.	Field / landscape scales.	Identify from photographic / satellite images the extent of landslides.		All the advantages described for soil apply.	Disadvantages are similar to those for soil.	
	Potential landslide risk products.	National Scale.	A series of static geological based products assessing the potential risk	These include: Susceptibility of landslides, Debris flow, landslide		Static and therefore not dynamic.	

Method		Scale	Time scale	Description of method	Method advantages	Method limitations	References
			produced as a GEOSURE product.	database and coal field landslides.			
	Future possibilities.	National Scale.	BGS has started using antecedent rainfall as a predictor for landslides, and sending warning e-mails to category 1 and 2 responders. This has been developed for Scotland only at the moment.		Potential exists for developing for Wales if suitable data available.		E.g. Pennington et al. 2014.

2.2 Costs associated with Methodologies

When determining the costs of a likely erosion monitoring programme, an outline of what the survey would entail is needed, including the aims, the land-uses it is going to cover and how it is going to report erosion changes in a meaningful way. Recent DEFRA reports (SP1303 and SP1311) have attempted to address these issues. Thus, the section below contains an outline of the issues discussed in these reports and have been used as a basis for providing 'example costs' for the ERAMMP project. However, it must be stressed that a bespoke statistical and methodological examination would be required for Wales and would constitute one of the costs.

Some Considerations for Statistical Design

Prior to any monitoring programme it would be expected that a series of questions would need to be considered to identify specific needs of the survey and how they may be implemented. A preliminary search for all information relating to soil erosion in Wales would provide a basis for making decisions especially developed as a GIS.

De Gruitjter et al. 2006 identified some principals to be considered when designing a monitoring programme and these would also apply to a Welsh soil erosion monitoring programme. These are outlined below

1. What is the design and specification required for the programme to consider
    a. The spatial area (e.g. Wales).
    b. The length of time soil erosion is to be monitored.
    c. The soil landscape and the land-use (e.g. what is the soil type distribution and the broad land use categories (e.g. arable, grass, forest) that are under consideration).
    d. The target variable to be examined (e.g. soil erosion (t ha^{-1} yr^{-1})).
    e. The target parameter e.g. changes in soil erosion over different time periods (short and long term).
    f. The target quantity.
    g. Type of result required (e.g. quantitative measurement).

2. The quality measure of the monitoring (e.g. 95th confidence interval around the estimated mean change for each land-use type).
3. Constraints – a range of constraints exist for monitoring programmes and include cost, land access, technological and analytical constraints.
4. Information which may aid the design of the survey should be collated (e.g. GIS, Soil Survey info regarding soil type, LIDAR and DEM data, existing erosion measurements).
5. Sample support (e.g. field or hectare).
6. Assessment method (e.g. what are the methods to be used).
7. Is composite sampling involved (e.g. if using cores taken for ^{137}Cs analysis).
8. Design based or model based inference – a model based analysis would suggest that a geostatistical approach could be taken using the co-ordinates of erosion events. However, because many soil erosion events (gullys, rills) are most likely driven by spatially limited and temporally (short) events (e.g. heavy localised rainfall) a design based approach is likely to be more suitable. This would be based on probability or random sampling.
9. Sampling design type – having decided that (e.g. Random).

10. Identification of sampling sites (numbers and whether undertake repeat sampling).
11. Method of statistical inference.

Further questions would still exist regarding whether

1. Do you bias the sample selection towards soils that erode or do you pick representative samples from all texture classes.
2. Issues regarding sampling at fixed sites over a number of time periods.

On both these issues the recent DEFRA report (SP1303), offered suggestions as to how to address both these questions. Firstly with respect to repeat sampling, the authors examined work reviewed in Evans et al. (2002) where repeat sampling of a number of different soil transects took place across arable land in England and Wales, between 1882 and 1986. At present this is the only dataset available which facilitates this kind of analysis. The authors found that when comparing erosion rates between repeat samplings, little correlation existed between the initial and subsequent erosion estimates. The suggestion then is that erosion events may be linked intrinsically to weather events, and that whilst soil properties such as texture and % OC may help determine the erosive potential of a soil they are unlikely to contribute to correlations when erosion is measured at different times. The implication for an erosion monitoring system is therefore that there is no advantage in sampling at fixed sites and that independent sampling could be used.

Whereas it is known that some soil texture types (sand, silt) are more prone to erosion, a statistical review of data presented in SP1303 addressed this problem. Data from Evans (2002) again was used, with the first erosion measurement from each of the 1277 sites used. Soil textures for each site were identified from the SSE&W datasets. Statistical analysis of the data showed that the null hypothesis – "that the three texture classes defined did not differ with respect to mean transformed erosion rate" - could not be rejected. Therefore, no further consideration was considered to a sampling design where there was stratification based on soil texture.

The final stage of looking to design a monitoring programme is then to assess numbers of samples. Again DEFRA Report SP1303 examined this using a "Power Analysis", again based on the data from Evans (2002). The requirements for the "Power Analysis" that the authors suggested were as follows:

1. To consider estimating the mean difference in erosion rate between two dates, by independent, simple random sampling.
2. The data was transformed, so the task is defined to detecting an underlying proportional change of *k* in the geometric mean erosion rate, i.e. a change of $\log_e(1+k)$ on the log-scale. Therefore the power for a two-sample *t*-test specifying s^2 (simple random sampling) was determined as the variance of the data. This was specified as a two-tail test (both increases and decreases in erosion are of interest), and at a significance level of 0.05. The power is the probability that a significant change could be detected (two-tailed test, significance level of 0.05) as an underlying change of $\log_e(1+k)$ on the log scale with a sample of specified size.
3. Common target 'Power' of 80% was used.

The results of this 'Power Analysis' suggested that a sample size of about 300 samples would be required to be 80 % confident that the survey would be able to detect a 50% increase in erosion rate (two date comparison) and between 900-1000 samples to detect change of 25% increase.

The costs produced below are based on the experiences of running a pilot soil monitoring programme reported in DEFRA report SP1311, between the years 2014-2016. These therefore represent reasonably accurate assessments of the labour hours required to undertake specific parts of the survey. We have included staff costs based on BGS 2018 FEC rates:

1. Collation of existing data with respect to soil erosion in Wales. This could be expanded to England as well if data is limited. Preparation of GIS.

   Time & Costs: 2 weeks at Band 6

2. Statistical Design of potential monitoring scheme.

   Time & Costs: 2 weeks at Band 5

3. ^{137}Cs survey of fields for soil and tillage erosion.

   Based on sampling clusters of 5 points, coring and analysis with 5 clusters per site. In addition reference sites needed so therefore potentially 10 clusters per site. Each core likely split into 3 (0-20cm, 20-40cm, >40cm). In DEFRA report SP1311, an indication of time requirements to sample and analyse ^{137}Cs samples was given for 17 sites. This included 765 hrs on fieldwork and 1524 hours on laboratory analysis. At NERC Band 6 pay scales (£434 per day FEC) this would come to ~£44866+89380 = £134246. Thus 300 sites (without T&S and consumables etc.) would amount to approximately £2,369,047.

4. Example costs of survey using different techniques of LIDAR and photogrammetry for rill and gully erosion monitoring:

In DEFRA report SP1311, the following man hours were described to undertake surveys in a range of upland areas in the UK. It is important to note how the costs of ground based photography are significantly higher because of the number of photos required, suggesting that this technique is more suitable for small areas where more complicated patterns of erosion are present.

Table 2: Costs associated with several techniques based on outcomes from DEFRA report SP1311

	UAV structure from motion photogrammetry (person-hours)		Terrestrial LIDAR Systems (person-hours)		Ground based Photography (person-hours)	
	per site	per ha surveyed	per site	per ha surveyed	per site	per ha surveyed
Field data capture	10.4	3.5	6.5	1.9	5.0	77.4
Post-processing CPU time	2.6	0.9	13.3	3.9	39.4	606.0
Post-processing person time (DTM creation, digitising, geo- referencing etc.)	3.0	1.0	6.9	2.0	3.2	49.6
Mean person time per technique	13.4	4.5	13.4	3.9	8.2	127.0
Costs at NERC band 6 (2018)						
Approx. cost of equipment (incl. hardware and software)	£1,500		£60,000		£750	

5. Costs of aerial photography:

For the identification of potential sites for selection for further work, or Evans (2002), reported on the time taken to survey and identify eroded fields from aerial surveys. They suggested that it took between 4-7 working days to view the aerial photographs of ~700 km^2 (Band 6 rates for 7 days this would equate to approx. £3100). Wales has an area of 20,779 km^2. However, it is now possible to automate the process which has the potential to reduce the costs. For example, automated classification of bare soil has been determined on the Welsh Government catalogue of aerial photography in conjunction with ENVI remote sensing software.

6. Satellite imagery costs:

The best use of satellite imagery is probably to identify areas experiencing erosion and the how the eroded area is increasing / decreasing over time and in relation to individual weather events of periods. There is a mix of satellites that could be used and access to data is either free or would be supplied at commercial costs.

a. The European Space Agency (ESA) Sentinel 2 satellite is free with a pixel size (resolution) of 10m x 10m. A requirement would be to download and process a whole or part of an image which is normally 290 x 200 km wide before rectification and selection of the tract of land desired to select sites. The process to download, rectify and produce the image in a GIS or other software package (e.g. ESA SNAP toolbox, or other purchased software such as eCognition or ENVI) is likely to take about 0.5 days per image. Archive samples are available for free. Examination of images would probably be similar to those of aerial photography as described above or the process could now be automated saving costs.
b. High resolution satellite – for example Worldview 3 (by Satellite imaging Corp) provides much greater resolution (31 cm in Panchromatic mode or 1.5m in multispectral mode). Swath width is 13km but this is usually part of a wider series of swaths. Commercial costs are in the several thousand £s per image. A further option could be from Planetscope which is a subscription satellite image service at 3m resolution flown every 2-3 days, but is expensive. Similar to aerial photography automated analysis can be implemented.

2.3 Can new technology be used to help monitor soil erosion

Section 2.1 has demonstrated the advantages and disadvantages associated with a wide range of techniques used to measure or predict soil erosion. Factors effecting soil erosion both temporally and spatially within the soil landscape, have demonstrated the need for this wide range of techniques. Section 2.2 has provided some evidence of costs, based on a sound statistical basis, and then practiced in a pilot study (DEFRA, SP1303 & SP1311). Costs for those techniques where a large number of man hours are required are obviously high. However, some new technologies should and can be considered within a design of a soil erosion monitoring programme, especially within a multi-technique approach which may encompass a series of scales from national to field-scale to answer a range of different questions.

From the review of literature assessing techniques to measure soil erosion at field-scale and in terms of determining losses (t ha yr^{-1}), perhaps the most robust methodology is the walk-over survey and volumetric measurement as carried out in the late 1980's by the Soil Survey of England and Wales (e.g. Evans et al. 2017). This type of survey could be updated to include assessment via the use of UAV along with digital photography. In DEFRA report SP1311, this technology was found to be as accurate as Terrestrial LIDAR analysis, and the staff cost in time and equipment is low, compared to other techniques. After site selection within a soil monitoring programme, the use of satellite image archives, along with weather archives could provide longer term data with respect to building up knowledge of soil erosion behaviour at sites (e.g. erosion events after periods of rainfall), with UAV monitoring occurring on a yearly basis to measure erosion rates. Geo-referenced imagery will allow calculation of upslope contributing areas and slope within GIS formats. Some ground-truthing using terrestrial LIDAR may initially be required to check for accuracy and the drone operators will need to be trained initially.

Traditionally, satellite imagery applications have been used to identify areas of soil erosion or bare soil. These indices along with other GIS based geomorphological indices (e.g. slope characteristics, upslope contributing areas) have been used to classify erosion severity but really only with respect to gullying (Separu and Dube, 2018). However, the use of a soils spectral reflectance (in the near IR) could indicate the extent of soil disturbance and allow the identification of rills, sheets and gullys (Separu and Dube, 2018). The spectral signature comes from mineral composition, organic matter, texture and moisture and the linking to erosion is via inference rather than direct measurement. However, with the increasing development of machine learning there is possibility that algorithms can be developed so more rapid assessments of larger areas could be undertaken. However, this would require some quite large areas to be investigated and mapped so that learning datasets could be developed.

Models are useful for answering the big questions concerning soil erosion on a national scale. For example, for assessing the effects of subsidy policy changes (e.g. more grassland being ploughed). National scale modelling has been undertaken for England and Wales recently in respect of climate change (Cooper et al. 2010) and separately for Wales for the GMEP project (unpublished data). An annual assessment of predicted water erosion for Wales is shown in Figure 2 based on the PESERA model (Kirkby et al., 2008).

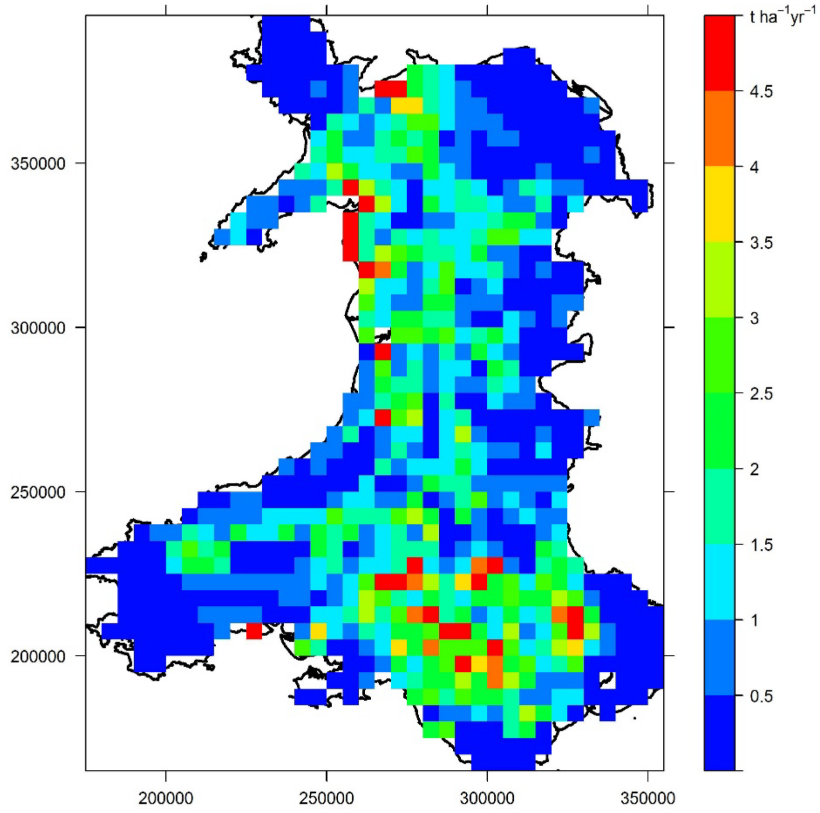

Figure 2: Predicted water erosion using the PESARA model for Wales.

3 Conclusions

1) The loss of soil resource through erosion has a wide range of impacts beyond the agricultural production. These include aquatic ecosystems and can cause sedimentation in water courses.
2) Because of the complexity of soil erosion and the different spatial and temporal scales that it operates over and the different techniques required to monitor the effects produced it is suggested that a multi-layered approach may be needed.
3) For drivers that may cause national scale changes in agriculture practice (climate, agricultural support payments) predictive models can provide evidence of the direction of travel.
4) Photo / satellite image surveys provide an excellent means of identifying where erosion is occurring and can be linked to landscape and land-use factors. This provides a means of identifying causes and producing mitigation strategies. A combination of both aerial and satellite imagery could be combined to provide a longer time series.
5) It is suggested that some ground truthing/measurement will need to be undertaken and this may involve a combination of terrestrial LIDAR and UAV photogrammetry.
6) These remote sensing techniques are highly appropriate to assessing bank erosion and landslides, over spatial and temporal scales.

4 Recommendations

The reviews of soil erosion in Wales (Boardman and Evans, 2006 and Morgan 1985) indicate that soil erosion in Wales is mainly attributable to upland erosion processes, e.g. peat, landslips and stream bank erosion, and water erosion along the border with England. Identifying the occurrence of hotspots for landslips and bank erosion, and erosion in peatlands would offer perhaps the most cost effective assessment of dominant erosion processes. Here we provide an estimate of sample size and cost of one potential approach. Adopting a modelling framework that could be developed for Wales would provide a useful baseline against which to compare data, scoping this between erosion specialists and WG and NRW would be beneficial.

4.1 Targeted monitoring linked to the ERAMMP survey

1) A review is carried out of landslip occurrence in Wales and identify locations and hotspots using an air survey, based on satellite data to identify bank erosion hotspots. This could be ground truthed in the uplands using the head water streams survey as part of the ERAMMP survey. (ca. £40k)
2) Undertake an air survey, based on satellite data to identify erosion hotspots in peat areas. This could be ground truthed in the uplands using surveyors to identify locations and confirm during the ERAMMP survey. (ca. £30k)
3) Consider the potential for citizen science to report bank erosion or landslips (e.g. building on a new app under development at CEH for recording land cover and soil threats. The app will be free and work off line with data available to WG approved researchers). (ca. £10k)
4) Organise a scoping meeting to explore options for developing a modelling framework for assessing soil erosion in Wales. (ca. £4k)

The above would provide a comprehensive assessment of the state and potential change of targeted erosion processes in the uplands and along rivers across Wales at a start-up cost of £84k. It would link with both the head water stream survey and the assessment of peat condition from surveyor data. The citizen science aspect offers potential for obtaining low cost future evidence.

4.2 National Soil Erosion Monitoring in Wales using Caesium

When determining the costs of a likely erosion monitoring programme, an outline of what the survey would entail is needed, including the aims, the land-uses it is going to cover and how it is going to report erosion changes in a meaningful way. Recent DEFRA reports (SP1303 and SP1311) have attempted to address these issues and provide guidance on what a full monitoring programme for Wales might require.

Statistical design is best using a power analysis, the results of which suggested that a sample size of about 300 samples would be required to be 80 % confident that the survey would be able to detect a 50 % increase in erosion rate (two date comparison) and between 900-1000 samples to detect change of 25% increase.

In DEFRA report SP1311, an indication of time requirements to sample and analyse ^{137}Cs samples was given for 17 sites. This included 765 hours on fieldwork and 1524 hours on laboratory analysis. At NERC Band 6 pay scales (£434 per day FEC) this would come to ~£44866+89380 = £134246. Thus, 300 sites (without T&S and consumables etc.) would amount to approximately £2,369,047.

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Enquiries to:
ERAMMP Project Office
CEH Bangor
Environment Centre Wales
Deiniol Road
Bangor
Gwynedd
LL57 2UW
T: + 44 (0)1248 374528
E: erammp@ceh.ac.uk

www.erammp.cymru
www.erammp.wales