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Interactions of Soil Hydrology, Land Use and Climate Change and their Impact on Soil Quality (SoilH)

STRIVE

Environmental Protection Agency Programme

2007-2013

SSTI Strategy for Science, Technology and Innovation

Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

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Executive Summary

The quality and characteristics of Irish soils are shaped not only by their parent geological material but also by climate and land use. This project has shown that the temperate, perennially moist climate in Ireland has the effect of maintaining and sustaining Irish soils at elevated soil organic carbon (SOC) levels, high levels of porosity and lower levels of bulk density than is the case in drier climates for similarly textured soils. This results in Irish soils having greater hydraulic conductivities than similarly textured soils in drier climates.

Grassland is the dominant land cover in Ireland, and this enables Irish soils to be protected and, to some extent, insulated from serious erosion, loss of organic matter and landslides. In many European Union (EU) countries, soil quality is under threat from a host of natural and anthropogenic activities. These threats include erosion, loss of organic matter (or SOC), compaction, surface sealing (or urbanisation) and landslides. The aims of this project were to attempt to quantify these threats across Ireland.

1. Contributing factors to erosion include heavily tilled, sandy soils with low organic content, mountainous areas with steep slopes, a climate with long dry periods followed by intense rainstorms, bare soil landscapes and the lack of perennial vegetative cover. Ireland has nearly 65% of its landscape covered with perennial grassland and a further 10% with established forests. This, in conjunction with the lack of widespread intensive agricultural practices and modest rainfall intensities, contributes to low levels of erosion at <1.0 t/ha/year and in-stream sediment yield at <0.2 t/ha/year, which is low by international comparison. However, erosion levels will increase in the future if significant increases in animal stocking density occur, as are called for in the Department of Agriculture, Food and the Marine report, *Food Harvest 2020*[1]. Expected increases in frequency and magnitude of extreme weather events (e.g. storms and droughts) are also likely to increase erosion levels.

2. This project sampled 31 mineral soil locations (three depths (0 cm, 15 cm and 30 cm) and three replicates) throughout Ireland. The sites were representative of the different soils in Ireland and were dominated by medium loams near the centre of the US Department of Agriculture (USDA) soil textural triangle. Bulk density, porosity, % sand, % silt and % clay (% SSC), % SOC and hydraulic conductivity and the van Genuchten water retention parameters were estimated. In estimating bulk density, the coarse fraction (>2 mm) was excluded, as is the globally accepted standard. The samples were coupled with those of an earlier EPA SoilC project[2] and found the following:

   (a) Gravimetric estimates of bulk density were always lower (for both topsoils and subsoils to 50 cm depth) than that estimated from textural analysis (http://www.pedosphere.ca). The authors attribute the low bulk density characteristic of Irish soils to the high SOC content, widespread grassland cover and perennial moist climate. This also contributes to higher than expected porosity with an abundance of soil macropores.

   (b) SOC levels were generally in excess of 2% and rarely fell below this. This makes Ireland unusual in its high SOC levels by international comparison. A contributory factor is the fact that 18% of the Irish landscape is covered in peat, where the % SOC is ~45%.

3. In-situ infiltration tests were carried out at all 31 mineral sites during the summers of 2008 and

1. Department of Agriculture, Food and the Marine, 2010. *Food Harvest 2020*. Available at: http://www.agriculture.gov.ie/agri-foodindustry/foodharvest2020 [accessed 18 August 2013].
2. Kiely, G., McGoff, N.M., Eaton, J.M., Xu, X., Leahy, P. and Carton, O., 2010. *SoilC Measurement and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils.* Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland.

2009, with the purpose of using the Beerkan Estimation of Soil Transfer Parameters (BEST) method to estimate the saturated and unsaturated hydraulic conductivity. However, as these two summers were unseasonably wet, it was not possible to estimate the unsaturated hydraulic conductivity and only the saturated hydraulic conductivity was determined. With a variant of the BEST method (known as the Wu method), the authors were able to estimate the water retention parameters. The estimates of saturated hydraulic conductivity ranged from lows of 2 cm/day to highs of ~ 2,000 cm/day or a range of three orders of magnitude. The range of hydraulic conductivities measured varied from some other international studies (Schaap and Leij, 2000[3]).

4. Erosion of SOC which ends up in suspended sediment in streams is of the order of 10 kg/ha/year. The SOC loss range is 2.5–4.5% of the in-stream sediment.

5. Carbon lost as dissolved organic carbon (DOC) in stream flow ranges from ~10 to ~150 kg/ha/year. Low levels are associated with catchments dominated by mineral soils, while the highest values are associated with streams in peatland catchments.

6. It was not possible to produce a hydraulic classification of Irish soils in accordance with the more widespread classifications of Schaap and Leij (2000)[3] or Clapp and Hornberger (1978)[4] using simple textural divisions and pedotransfer functions. The study data did not show significant difference among the conventional textural classifications. The aim was to identify a reliable classification that would maximise the difference in hydraulic properties between different textural classes but minimise the difference within each class. The Irish Forest Service (IFS) classification is suitable for Irish soils, which differ from soils in other climates due to the high SOC content and the perennial wet climate. Therefore, the study produced a quantifiable hydraulic classification similar to that of the IFS. The existing qualitative IFS classification cannot be used for hydrological modelling. However, the quantitative extension of the IFS classification in this study enables it to be used for hydraulic modelling purposes. The study's quantitative IFS classification is:

   - Deep, well-drained mineral soils; $K_s \approx 166 \pm 534$ cm/day;[5]
   - Shallow, well-drained mineral soils; $K_s \approx 22$ cm/day;
   - Deep, poorly drained mineral; $K_s \approx 7.8 \pm 6.8$ cm/day;
   - Poorly drained mineral with peaty topsoil; $K_s \approx 3.1$ cm/day;
   - Alluvia; $K_s \approx 14.2$ cm/day; and
   - Peats; $K_s \approx 1{,}030$ cm/day at bog centre and 1.03 cm/day at bog edge.

7. Detailed in-situ sampling was carried out at 14 locations within one pristine blanket peatland and it was found that the peatland catchment can be partitioned into two very distinct hydraulic areas, one close to the bog edges (e.g. near the draining stream) and the other representing the bog interior. The authors found that the bulk density varied from 0.055 g/cm^3 at the bog interior to 0.11 g/cm^3 at the bog edge. Peat profiles were sampled to depths of 5 m and no increase in bulk density with depth was found. It was found that the saturated horizontal hydraulic conductivity was approximately twice the saturated vertical conductivity. The saturated conductivity ranged from ~1.03 cm/day at the edge to ~1,030 cm/day at the bog centre, a difference of approximately three orders of magnitude.

8. The empirical erosion and sediment models, Revised Universal Soil Loss Equation (RUSLE) and Sediment Delivery (SEDD), were used at the catchment and national scales to estimate annual

3. Schaap, M.G. and Leij, F.J., 2000. Improved prediction of unsaturated hydraulic conductivity with the Mualem-van Genuchten model. *Soil Science Society of America Journal* **64(3):** 843–851.
4. Clapp, R.B. and Hornberger, G.M., 1978. Empirical equations for some soil hydraulic properties. *Water Resources Research* **14(4):** 601–604.

5. K_s, saturated hydraulic conductivity.

erosion and sediment yield. The parameters required for RUSLE and SEDD have not yet been experimentally determined for Irish conditions, as no dedicated erosion field studies have been carried out. However, the authors found, using literature parameters for RUSLE, that Ireland experiences low levels of erosion and loss of SOC.

9. Future scenario modelling using RUSLE and SEDD suggests that land use change, and not climate change, is likely to result in greater erosion and sediment delivery.

10. The use of the process-based rainfall/run-off model (at hourly scale) – GEOtop – with the new code for erosion and loss of organic matter developed in this project was used to estimate river flows, erosion and loss of SOC at the catchment scale. GEOtop was more successful at estimating erosion than RUSLE. This was due to the fact that GEOtop could be calibrated at the catchment scale. Furthermore, GEOtop was most successful where the rainfall data were most precise, typically with hourly rain gauges within the catchment. In contrast, the RUSLE uses only annual total rainfall amounts. GEOtop was used to model the following catchments: the Dripsey 15-km^2 grassland catchment; the 1-km^2 Glencar peatland catchment; and the three sub-catchments of the Munster Blackwater (245, 881 and 1,186 km^2). It was found that GEOtop modelled the stream flow well for all catchments. However, there are no measurements of erosion or SOC loss for the Munster Blackwater with which to compare the model results. The simulations show that as one moves downstream onto the flatter catchment areas with wide (~2 km) floodplains, the erosion increases. The authors consider that this increased downstream erosion is a product of increased areas of tillage and, in particular, floodplains that suffer frequent flood events (several times each year), leaving mobile sediment on the river banks readily available for transport downstream in the next flood. The only catchment for which detailed suspended solids yield (SSY) was available was the Dripsey, and GEOtop modelled the SSY of the Dripsey very well. Using GEOtop a number of additional exercises were carried out:

    (a) A series of GEOtop model runs on the Dripsey catchment showed that simulations of increased rainfall intensity resulted in dramatic increases of erosion and loss of SOC.

    (b) A further series of GEOtop runs in the Dripsey catchment, incorporating changes for compaction effects (e.g. increases in bulk density in conjunction with decreasing hydraulic conductivity), showed that simulations of increasing compaction resulted in significantly increased erosion and loss of SOC. River peak hydrograph flows were appreciably higher during flood flows under compacted conditions than under the non-compacted conditions.

11. Surface sealing (e.g. urbanisation, suburbanisation, infrastructural developments) has increased significantly in Ireland in recent decades and was estimated (using data up to 2006) as ~2.1% of the total land area of the Republic of Ireland. This compares with an EU range of 0.15% (Iceland) to 13.3% (Malta). By comparison, the values are 3.3% for the UK and 5.1% for Germany. It is important to reflect in spatial planning strategies that the loss of agricultural soil to surface sealing is irreversible, and likely to have long-term effects on agriculture, forestry and ecological soil functions (e.g. loss of carbon sinks). Furthermore, urban growth leads to reduced groundwater availability, and urban planners should consider no growth or reduced growth scenarios in areas dependent on groundwater. The recent urbanisation seems to have led to increased frequency of urban flooding, as documented for Douglas, Cork, in 2012 and elsewhere in Ireland in 2009.

12. The Geological Survey of Ireland (GSI) recorded 117 landslides by 2006 and 136 by 2009. This compares with almost 500,000 in Italy. Nearly half of the landslides in Ireland are in peatlands (63 of the 136). Contributing factors include rainfall patterns (e.g. wet periods following dry periods),

peat harvesting and construction activities. Although landslides can occur at any elevation, the authors found the factors most influencing landslides to be mountainous areas, a land cover of peat, and sloping land. Landslides tended to occur in clusters, in locations where the influencing factors were present. Landslides of mineral soils at cliffs and coastal areas due to coastal erosion are likely to become more significant in the future due to climate change, sea level rise and increasing intensity of storms and sea surge.

13. Soil compaction is considered to occur at two levels in the vertical soil profile: compaction of the topsoil (to a depth of ~20 cm) is considered reversible, and compaction at the lower depths to about 50 cm is considered irreversible. Soil compaction causes an increase in bulk density, a reduction in porosity (mainly reducing the number of larger soil pores), a reduction in hydraulic conductivity and altered water retention curve characteristics. Compaction thus results in lower crop productivity because of decreased rooting depth and more frequent anaerobic conditions in near-surface soils. Compaction causes a decrease in infiltration and an increase in overland flow, with higher fractions of rainfall becoming stream flow faster than in the case of uncompacted soils. Compacted soils thus result in greater erosion and higher losses of organic matter than catchments with uncompacted soils. This potential was verified using scenario model runs of GEOtop for the Dripsey catchment using increased values of bulk density and associated altered hydraulic soil properties. However, when the soil bulk densities at the 46 mineral soil locations of the EPA SoilC project[2], which had soil samples to a depth of 50 cm, were examined, no evidence of compaction in the topsoil was found. This was based on bulk density comparisons between those estimated gravimetrically and those estimated by textural analysis. On the contrary, the bulk densities in all topsoil samples were less than those estimated from textural analysis (% SSC). The authors consider that this is due to the loose, porous nature of Irish mineral topsoils, which are rich in organic matter (>2% SOC) and are perennially well watered with light to moderate rainfall, and due to the widespread grassland cover which is ploughed and reseeded every few years. Furthermore, the authors found for all topsoils and lower depth soils (to 50 cm) that the estimate of the soil porosity based on gravimetric data was higher than the porosity estimated from knowledge of texture only. However, only two of the 46 samples were found to be compacted at the deeper depth of 25–50 cm. These two sites were in arable land use.

14. In contrast to our EU neighbours, the authors find no evidence of widespread soil degradation across the sites examined. There is little evidence of widespread erosion or loss of SOC, and that which does occur is low by international comparison. Similarly, there is little evidence of widespread compaction of Irish grassland soils, and the naturally occurring perennial low-intensity rainfall and high levels of SOC, combined with the widespread land cover of grassland, seem to almost insulate Irish soils from compaction. Of the 136 landslides documented by the GSI, half are in peatlands and most are recent, and are attributed to climate effects, road construction and development. However, on the international scale (e.g. Italy has recorded more than 500,000), Ireland has few landslides.

Relevance to Policy

This report finds that the threats (erosion, loss of organic matter, compaction, surface sealing and landslides) to Irish soils under current land use, management and climate conditions are low by international comparisons. This suggests that Irish soil quality is sustainable as currently managed. However, there are potential risks to sustainability of soil quality associated with intensification of food production in Ireland. In this context, there is an immediate need for comprehensive research to address the impact on soil quality of the recommendations of *Food Harvest 2020*[1]. There is also an urgent need to address the potential impact of wind farm infrastructure on peatlands, and in particular on the structural integrity of peatlands.

Recommendations for Future Research

1. Since there is no field experimental research in Ireland on erosion, loss of SOC and compaction, the authors recommend that the EPA addresses field experimental research at the catchment scale (e.g. nested catchments). This will allow Ireland to contribute to its soil data commitments to the EU and also enable more robust modelling efforts using RUSLE, SEDD and process-based rainfall/run-off models (e.g. GEOtop) for Irish soils.

2. The authors recommend a small-scale field and laboratory campaign to examine the methodology of bulk density determination. Bulk density determined by excluding the >2 mm fraction is correct for carbon stock measurement. However, for hydraulic studies, some suggest that the soil fraction >2 mm should be included. It is important to know if there are significant differences between the values of bulk density for the two methods.

3. The authors recommend the extension of the SoilH and SoilC sites (to include both bulk density and SOC) to enable a better estimate of SOC stocks and stock changes.

4. There is a dearth of field data on Irish soils with regard to hydraulic properties, and the authors recommend a national-scale field campaign to determine the hydraulic properties of Irish soils on the scale of the National Soils Database (NSD) project.

5. A spatially explicit experimental and model study is required for predicting peat depths.

6. While rainfall extremes and flooding were not in the brief of this project, these extremes may be the cause of much greater threats to soils than the threats that were examined in this report. Land use change in Ireland (particularly urban/suburban) suggests that more research about surface sealing impacts on hydrology and groundwater resources is required. The authors recommend that the EPA addresses rainfall extremes with consequent threats of flooding as a potential threat to soils.

7. There is a multiplicity of agencies in Ireland involved in soil data, soil information and soil research. The authors recommend that a single national agency (e.g. the EPA) co-ordinate soil data, information and research, in anticipation of the EU Soils Directive.

1 Introduction

1.1 Brief Summary of Proposal

Threats to soil depend on soil type, type of land and changes in land cover, land management practices, topography, and climate. Eaton et al. (2008) estimated that the land cover of Ireland in 2000 was 63% grassland, 18% peatland, 9% forestry, 8% arable, and 1.6% urban/suburban. This percentage of grassland is much higher than in most other counties in the European Union (EU), while the percentages of arable land and forestry are much lower. The temperate Irish climate has a mean annual temperature of ~10°C (with a monthly range of ±7°C). The island average annual rainfall of ~1,000 mm (range 700–1,400 mm) is high but the intensity of rainfall is not severe. While Ireland can be described as ‘hilly’, the highest mountains at 1,000 m are low relative to most other countries. The dominant grassland cover on lands with elevation mostly lower than 200 m and a temperate rainfall suggest that Ireland is unlikely to suffer significant soil degradation from erosion, losses of organic matter (OM), compaction, or landslides. On the EU scale of surface sealing (urbanisation/suburbanisation), Ireland, with 1.6% of its land area sealed, is on the lower end of the EU scale, the latter ranging from 0.15% to 13.3%.

Soils are a vital non-renewable resource that provide a range of economic and environmental services, including the support of food and fibre production, the control of water in the hydrologic system, the loss, purification, contamination and utilisation of water, the provision of habitats for organisms, the foundations for societal infrastructure (buildings, roads and bridges), and storage for carbon in the form of OM. Fertile soil is essential to food security and human health, and therefore must be protected (CEC, 2006). At the EU level, there have been a number of important initiatives including the *Thematic Strategy for Soil Protection* (CEC, 2006) and the *Soils Atlas of Europe* (A. Jones et al., 2005). The *Thematic Strategy for Soil Protection* identified soil degradation as a serious problem in Europe. It states that this is “*driven or exacerbated by human activity such as inadequate agricultural and forestry practices, industrial activities, tourism, urban and industrial sprawl and construction works*”. Such degradation reduces the ability of the soil to perform essential functions, reducing fertility, carbon, and biodiversity, and water retention capacity. In addition, increasing trace gas atmospheric concentrations (e.g. CO_2, CH_4 and N_2O), disruptions to the nutrient and biogeochemical cycles and less degradation of contaminants compromise key soil functions. The *Thematic Strategy for Soil Protection* further states that “*Soil degradation therefore has a direct impact on air and water quality, biodiversity and climate change. It can also impair the health of European citizens and threaten food and feed safety*”.

1.2 Aims and Objectives

The aim of this research is to examine the risks posed to Irish soils, in the face of changes in land use, land management and possible shifts in climate. To understand how these pressures affect soil quality, we need to understand how they will affect the key quality functions: regulating water infiltration and flows through watersheds, sustaining plant productivity, mitigating pollution influences, supporting the sustainable cycling of nutrients, and supporting engineered structures. This project is a study of the interactions of soil hydrology, land use and climate change and their impacts on soil quality. The task is to examine the threats posed to soil quality under current and possible future land use and climate, and include the following:

1. To conduct a review of the literature on threats to soil;

2. To carry out field sampling to estimate the hydraulic characteristics of a range of Irish soils;

3. To use Task 2 (above) to develop a hydrological classification of Irish soils;

4. To identify a small number of representative Irish river catchments for river rainfall/run-off modelling as a precursor to modelling erosion and loss of

OM;

5. To develop new software modules as add-ons to the existing physically based process rainfall/run-off model GEOtop, and so enable hourly modelling of Irish river catchments in terms of the three threats: erosion, loss of OM, and compaction;

6. To use GEOtop to examine future scenarios of land use and climate change on the threats to soils – erosion, loss of OM, and compaction;

7. To use the Revised Universal Soil Loss Equation (RUSLE) (for erosion) and Sediment Delivery (SEDD), in conjunction with a geographic information system (GIS) and spatially available data sets for Ireland, to estimate current erosion and sediment delivery quantities at the annual scale, for representative Irish catchments and for Ireland in general;

8. In addition, to use RUSLE and SEDD to examine the erosion and sediment delivery threats posed under possible future land use and climate change scenarios;

9. To use GIS and currently available data sets to update estimates of surface sealing (urbanisation/ suburbanisation) in Ireland;

10. To use GIS and available data sets to develop a risk assessment tool for the threats of landslides; and

11. To write a final report and publish papers, two PhD theses and a Master's thesis.

1.3 Literature Review

1.3.1 Soil threats

Land use, farming systems, and agricultural practices may strongly affect soil water flow, soil erosion and OM loss. In the light of climate change, an increase in the frequency and duration of dry periods (droughts) is expected as well as increasing precipitation amounts and intensity and extreme events (floods) in many areas of the world (IPCC, 2001). Consequently, there are increased risks of landslides and soil erosion with implications for loss of OM. Climate change in Ireland is predicted to incur an increase in temperature for all months of between 1.25 and 1.5°C, a decrease in summer precipitation (of ~10%), and an increase in winter precipitation (of ~15%) for the 2021–2060 period (McGrath and Lynch, 2008). This increasing precipitation trend has already been detected in the west of the country since the mid-1970s (Kiely, 1999; Leahy and Kiely, 2011). Significant land use change may be about to occur on agricultural soils, if the projections of *Food Harvest 2020* (DAFM, 2010) are to be realised. In an ambitious plan to increase the national income from agriculture, *Food Harvest 2020* calls for an increase in the animal herd numbers (beef, cows, sheep, etc.) by as much as 50% by 2020. This huge increase inevitably will impact soil and water quality, the implications of which have not yet been studied in detail. Soil sealing falls under two classes: *urbanised surface sealing* and *compaction*.

1.3.1.1 Soil sealing – urbanisation and suburbanisation

This project explicitly addresses the first class of sealing, and leaves the second class to be treated within the *soil compaction* analysis. A recent study from EU DG Environment (EEA, 2012) examined the extent of urban surface sealing, and found levels of 13.27% (Malta) to 0.15% (Iceland), with 7.37% (Belgium), 5.07% (Germany), 3.53% (Denmark), 3.34% (UK), 1.59% (Ireland) and 0.37% (Sweden). According to an Irish study by Eaton et al. (2008), the percentage area of urban-only land in Ireland continuously increased from 0.15% in the year 1901 to 0.40% in the year 2000. Of the total land area of the Republic of Ireland, Eaton et al. (2008) estimated that the suburban extent was 1.26% in 2000, while the urban extent was 0.40%. The combined urban plus suburban extent of 1.65% is similar to the estimate of 1.59% by other sources (EEA, 2012).

1.3.1.2 Soil compaction

Soil Science America defined soil compaction as "*the process by which soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density*". Soil compaction is a form of physical degradation resulting in densification and distortion of the soil matrix, whereby biological activity, porosity, macroporosity and permeability are reduced, density and strength are increased and the natural soil structure is partly destroyed. Compaction reduces water infiltration capacity (by reducing the large pores) and increases the erosion risk by increasing the amount of surface run-off. The compaction process can be initiated by wheels, tracks, rollers or the passage of animals. Common agricultural practices, including tillage, fertilisation or grazing, can cause soil compaction. Overuse of machinery, intensive cropping, short crop rotations, and intensive grazing lead to soil compaction, which is exacerbated when these activities are carried out on soils with low soil OM (Hamza and Anderson, 2005). OM helps to retain soil water, thus enabling soils to rebound against compaction. Maintaining an adequate amount of OM in the soil stabilises soil structure and resists degradation. It is considered that OM binds soil mineral particles, reduces aggregate wettability, and influences the mechanical strength of the soil aggregate (Hamza and Anderson, 2005).

Topsoil compaction occurs to a depth of approximately 20–30 cm. Subsoil compaction is found at depths below 30 cm. Farm machinery travelling on wet soils exacerbates both topsoil and subsoil compaction. Topsoil compaction is caused by ground contact pressure and is the pressure exerted by the tyre or track. Reducing contact pressure results in less topsoil compaction, and travelling on dry soils is considered to have little or no impact on topsoil compaction. Furthermore, topsoil compaction is considered to be reversible by ploughing, where the soil is loosened and soil aggregate stability is enabled to return to the topsoil. Subsoil compaction, below 30 cm, is due to excessive axle loads and may be irreversible. Axle loads greater than 5 t are considered to induce subsoil compaction. In general, soil testing in situ or in the laboratory (for bulk density) is required to determine the level of compaction. As compaction increases bulk density, reduces macroporosity and reduces the saturated moisture content level, the pre- and post-compacted soil have different water retention curves and different hydraulic conductivity characteristics. Assouline (2006a) noted that soil bulk density can reflect the extent of soil compaction, and can also be related to the effects of soil compaction on soil hydrological behaviour, and he proposed empirical approaches to quantify and predict the effects of compaction on changes of bulk density and thereby on water retention and hydraulic conductivity (Assouline, 2006a,b). Soil compaction increases bulk density, which decreases the hydraulic conductivity, and induces earlier saturation levels (with regard to the water retention curve). The more compaction there is, the greater are the effects. The saturated hydraulic conductivity (K_S) is mostly determined by the large pores, which are reduced (in number and size) when the soil bulk density increases, and consequently the K_S of a soil is reduced by orders of magnitude on compaction (Horton et al., 1994). Assouline (2006b) suggested that the ratio of compacted saturated hydraulic conductivity (K_{SC}) to initial conductivity (K_S) was a function of the ratio of compacted to initial porosity and to the ratio of compacted to initial bulk density. For instance, for a bulk density ratio of ~1.1 (post-compaction density to pre-compaction density), the saturated conductivity ratio is ~0.5 (K_{SC}/K_S); for a bulk density ratio of ~1.2, the saturated conductivity ratio is ~0.2; and for a bulk density ratio of ~1.4, the saturated conductivity ratio is ~0.05. As Ireland has >60% land cover of grassland, managed for cattle grazing and silage production, and soils with >2% soil organic carbon (SOC), such land use management is likely to have limited compaction effects. However, the tillage fraction (a user of heavy machinery) of Irish agriculture (at ~8% of Irish land use) and dominantly in the east and south-east of the country, where SOC values are typically ≤3%, is likely to experience compaction.

1.3.1.3 Soil erosion

The authors define the terms ‘erosion’ and ‘sediment yield’ as follows:

- Erosion is the gross amount of soil detached from the land surface (e.g. grass field) with some fraction being reattached to a downslope area of the catchment and the remainder being transported down the slopes into a catchment stream outlet.
- Suspended solids (or sediment delivery) yield (SSY) is the amount of in-stream suspended sediment measured at this stream.

Erosion is higher than sediment yield, as a higher fraction of eroded material is deposited along the land slopes than is carried into the stream. To convert erosion amount to sediment yield amount, erosion is multiplied by a sediment delivery ratio (SDR), which is unique to each catchment and ranges from about 0.1 to 1.0. In the USA, the universal soil loss equation (USLE) was developed from field experiments of erosion for rain-induced erosion and is still, in its revised form (RUSLE), the basis for determining erosion from "*highly erodible lands*" for various United States Department of Agriculture (USDA) programmes.

The RUSLE equation is expressed as:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad \text{(Eqn 1.1)}$$

where:

- *A* is the estimated spatial average soil loss and temporal average soil loss in kilograms per unit of area, expressed in the units selected for *K* and for the period selected for *R*. This amount is then compared with the 'tolerable soil loss' limits or threshold to evaluate the soil loss severity;

- *R* is the rainfall/run-off erosivity factor, which varies by geographic location. The greater the intensity and duration of the rainstorm, the higher is the erosion potential;

- The *K* parameter is the soil erodibility factor, which is the soil-loss rate per erosion index unit for a specified soil as measured on a standard plot 22.1 m in length of uniform 9% slope in continuous clean-tilled fallow land. This factor is a measure of the susceptibility of soil particles to be detached and transported by rainfall and run-off. Texture is the principal factor affecting *K*, but soil structure, organic matter and permeability also contribute;

- *L* is the slope length factor, the ratio of soil loss from the field slope length to soil loss from a 22.1 m length under identical conditions;

- *S* is the slope steepness factor, the ratio of soil loss from the field slope gradient to soil loss from a 9% slope under otherwise identical conditions;

  L and *S* factors reflect the overall impact of the topography of a specific geographic area. The steeper and longer the slope, the higher is the risk for erosion;

- *C* is the cover management factor, the ratio of soil loss from an area with specified cover and management, to soil loss from an identical area in a tilled continuous fallow reference plot. The *C* factor indicates how the conservation plan will affect the average annual soil loss and how that soil-loss potential will be distributed in time during construction activities, crop rotations, or other management schemes; and

- *P* is the support practice factor, the ratio of soil loss with a support practice such as contouring, strip cropping or terracing, to soil loss with straight-row farming up and down the slope. It reflects the effects of practices that will reduce the amount and rate of the water run-off and thus reduce the amount of erosion. The most used supporting cropland practices are cross-slope cultivation, contour farming and strip-cropping.

Some land use and management practices can lead to precipitation-induced soil erosion, which in turn can deteriorate the remaining physical, chemical and biological soil properties, and as a consequence reduce soil productivity. The study by Van Oost and Govers (2006) showed that erosion rates in tillage land can exceed 10 t/ha/year, especially on fields with complex topography. Such rates are at least of the same order of magnitude as average water erosion rates reported for hilly cropland in Western Europe. Cerdan et al. (2006) noted that land uses with the highest percentage of bare soil have the highest soil erosion rates. Evans (1996) estimated that erosion significantly and adversely affects 40% of arable soils in the UK, with these soils having lost as much as 25% of their agricultural productivity. Off-site impacts of erosion include sedimentation of rivers and lakes, watercourse pollution and eutrophication, silt build-up in rivers with its consequent impact on young aquatic life, and perturbed functions of river systems (Owens et al., 2005).

As the dominant land use in Ireland is grassland, erosion in the form of particulate matter transports nutrients from the soil to the watercourses (Jordan et al., 2005; Scanlon et al., 2005). The lack of knowledge on soil erosion in the EU has been highlighted by Van-Camp et al. (2004). There is a lack of field experimental studies to quantify erosion rates from different land uses and different spatial scales in Ireland. Sediment loads in streams have been studied in Northern Ireland, but from the perspective of water quality rather than for their erosion or impact on soil quality (Evans et al., 2006). Related studies by Lewis (2003) measured suspended solids export from a nested set of small grassland catchments in the Dripsey, County Cork, where the SSY export ranged from 0.073 to 0.136 t/ha/year for 2002. Harrington and Harrington (2011) measured the SSY from two Irish rivers and found SSY of 0.142–0.256 t/ha/year for the 105 km^2 Owenabue River and the 608 km^2 Bandon River in County Cork, respectively. During the EPA STRIDE Lee Valley Study (1993–1994) (Tunney et al., 1997), the total SSY exports were estimated from grassland agricultural land in the Dripsey, based on continuous stream discharge measurements and an intensive water sampling programme. Measurements were made at three catchment scales (2.28 km^2, 14.91 km^2, 88 km^2) and annual SSY exports of between 0.127 and 0.24 t/ha/year were estimated. If we assume that the mean SSY in these catchments was 0.2 t/ha/year and further assume an SDR of ~0.5, then the erosion rates of these small grassland catchments were ~0.4 t/ha/year. Verstraeten and Poesen (2001) found that the SSY export ranged from 0.50 to 26.0 t/ha/year for intensively cultivated small catchments in a humid temperate climate of Belgium and found a global range of three orders of magnitude for SSY of 0.02–20 t/ha/year by comparison with the observed Irish magnitudes of the order of ~0.2 t/ha/year. Land use is clearly a most important control on erosion (Cerdan et al., 2010), with bare soil (tillage and vineyards) having highest erosion rates (3.6–17.4 t/ha/year) and permanent vegetation (shrub, forest and grassland) having erosion rates less than 1 t/ha/year.

1.3.1.4 Loss of soil organic matter

In discussing the loss of soil organic matter (SOM), we can interchangeably discuss the loss of SOC, as in general SOC $\approx$ 0.45 SOM. SOC lost from the land surface to the aquatic system is found in the form of carbon in suspended sediment or carbon as dissolved organic carbon (DOC). SOM is the organic matter component of soil. It is as high as 90% in peatland soils and as low as <1% in mineral soils. In Ireland, peat soils contain ~35–50% SOC; organic soils are defined as those with an SOC > 12%; mineral soils contain SOC up to 12%. Overuse of soils, as in intensive tillage practices, tends to result in the reduction of SOC. Soils in the south-east of Ireland, where tillage dominates, have an SOC as low as 1%. SOM contains more than three times as much carbon as either the atmosphere or terrestrial vegetation, so caretaking this huge carbon resource is vital, particularly as climate change may negatively impact the stock and stock changes of SOC. Most of the SOC is found in the topsoil (0- to 20-cm depths), and it is seen as a measure of soil quality and productivity. Increasing SOC is considered desirable from both an agricultural and from a carbon sequestration perspective, the latter being considered as a greenhouse gas (GHG) mitigation strategy. A. Jones et al. (2005) and R.J.A. Jones et al. (2005) maintain that 0.6% of soil carbon in EU terrestrial systems is being lost annually. The concern is that decreasing SOC reduces land productivity and impairs the physical processes (e.g. infiltration capacity) and nutrient cycling mechanisms. Van Beek and Toth (2012) note that, in the EU, most soils are out of carbon equilibrium as regards SOC, as they have been affected by land management practices and land use change. Assessments of changes in SOC suggest that, in cropland in particular, carbon stocks are generally in decline. In modelling studies of the loss of soil carbon, once the erosion loss is estimated, the loss of SOC can be estimated by multiplying the erosion loss by an enrichment ratio (ER), typically about 3.5%. The ER is defined as the ratio of the SOC concentration in suspended sediment to the SOC concentration in topsoil. Cogle et al. (2002) found an ER of 2.5% ± 1% in semi-arid soils in India. Based on 10 years of erosion data from the Woburn Erosion Reference Experiment, Bedfordshire, UK, Quinton et al. (2005, 2006) showed that the total amount of carbon removed via erosion as particulate organic matter from individual arable plots ranged from 7.6 to 31.2 kg C/ha/year over the 10-year period. Enrichment ratios range from as low as 1% to highs of about 5%. The higher ER values are in loose soils on steep ground.

The annual export of DOC measured by Koehler et al. (2008) was 141 kg C/ha/year from a blanket peatland in County Kerry, which was strongly influenced by the high rainfall (~2,500 mm/year) in the catchment. The study in Ireland by Kiely et al. (2010) in an EPA-funded SoilC project, noted that the DOC concentrations ranged from 0.9 to 25.9 mg/l and varied temporally due to the effect of discharge and temperature/biological processes. The DOC export from 55 Irish streams was estimated to range from 11 to 156 kg C/ha/year. The annual DOC exports were found to vary with land use, with peatland catchments exporting three times as much as arable (this was mainly due to the high run-off in the peatland catchments and not necessarily high DOC concentrations). Although land use is not the primary factor controlling DOC exports, annual DOC exports decrease as the percentage of arable lands in the catchment increases, and DOC exports increase as the percentage of peatland in the catchment increases. The type of soil drainage class (e.g. shallow, well-drained soils), rather than soil type, better explains the variations found in DOC exports. Peat soils export more DOC than either podzol or deep, well-drained mineral soils. Koehler et al. (2008) generalised that DOC concentrations in organo-mineral catchments seem to depend on stream flow, while in temperate peatlands the main driver for seasonal variations in DOC is temperature. At this point, it is relevant to compare losses of SOC and DOC. Quinton et al. (2006) estimated losses of 7.6–31.7 kg SOC/ha/year for a number of arable plots in the UK.

1.3.1.5 Landslides

In Ireland, landslides in mineral soils are rare and, when they occur, they tend to be associated with earthworks, overgrazing by sheep on steep landscapes, areas with shallow topsoils, river or coastal erosion. Landslides in peat soils, however, are much more common in Ireland and Scotland (Creighton, 2006; Dykes and Warburton, 2007, 2008). The landslide study in peat by Warburton et al. (2004) indicated that most instability was related to convective summer thunderstorms and distinct drainage features. At the scale of the soil profile, the special hydrological properties of peat, in particular near surface water tables all the year round, and hydraulic conductivity offer important clues to failure mechanisms. The Geological Survey of Ireland (GSI) published an inventory of landslides in Ireland (Creighton, 2006), which is regularly updated. By 2010, there were 136 recorded landslides in Ireland, with more than half in peatlands.

1.3.2 Hydrological classification of Irish soils

Soil–water interaction is the common denominator for the set of threats to soils (erosion, loss of OM, surface sealing, compaction and landslides). The hydrological behaviour of the soils is the stage on which the climate and land use changes interact. However, these interactions over time can cause significant structural changes to the hydrological behaviour of soils. It is thus necessary to synthesise a hydrological classification of Ireland’s soils from various soil hydrological properties (SHPs).

1.3.2.1 SHPs

The SHPs of interest are the:

- Soil water retention curve; and
- Soil hydraulic conductivity curve.

The soil water retention curve is the relationship between the water content, θ (usually on the horizontal axis), and the soil water potential, ψ. When a soil is saturated, it holds water via capillary forces and its potential is close to zero. When a soil is close to wilting point (or drought), the small amount of water in the soil is held tightly to the soil particle surfaces by adsorptive forces and its potential is high, ~1.5 MPa (~15 hPa). The water retention curve is different for different types of soil, and is also called the soil moisture characteristic. It is used to estimate the soil water storage, water supply to the plants (field capacity) and soil aggregate stability. Sandy soils involve mainly capillary binding, and therefore release most of the water at higher potentials, while clayey soils, with adhesive and osmotic binding, will release water at lower (more negative) potentials.

The soil hydraulic conductivity curve is the relationship between the moisture content of a soil and the speed at which water can flow through the soil. When the soil is saturated, the hydraulic conductivity is at its highest value and is known as saturated hydraulic conductivity.

Once the latter is known, the hydraulic conductivity at lower moisture levels relates to the saturated value. These SHPs are a requisite for modelling rainfall/run-off, modelling water and solute transport, managing irrigation and drainage problems, coupling precipitation and run-off in climate and hydrology models, process-based modelling of erosion and loss of OM, and determining the hydrological import of surface sealing or urbanisation of catchments. Soil hydrological characteristics in saturated and unsaturated soil zones can be measured experimentally (in situ or in the laboratory) and/or estimated using mathematical or statistical models (i.e. pedotransfer functions, PTFs). Determination of soil water characteristics is time and labour consuming and requires the use of expensive and specific equipment. Therefore, methods for the estimation of the SHPs have generated many semi-empirical and statistical equations (e.g. PTFs) describing the water retention curve (Kutilek and Nielsen, 1994). These equations contain parameters that generally have little direct physical meaning and are mainly used as fitting parameters to match a function to experimental data points. The most common parameterisation of the hydraulic properties in mathematical models for flow and transport in porous media is now the van Genuchten–Mualem (VGM) formulation.

1.3.2.2 Classification of SHPs

Using the concept of PTFs, Clapp and Hornberger (1978) proposed a simple power-law descriptor of SHPs to maximise parameter identifiability, and for strongly tying hydraulic parameters to soil texture (i.e. pore size distribution). They demonstrated this approach for 11 soil textural classes in the US, providing mean and standard deviations for each parameter for each soil class. Their power curve representing the soil water retention curve (moisture characteristic) is:

$$\Psi = \Psi_S W^{-b} \qquad \text{(Eqn 1.2)}$$

The soil wetness is $W = \theta/\theta_S$ where θ_S is the saturated water content or likely the porosity. Both Ψ_S (the saturation suction) and b must be estimated, but are considered constant properties of the individual soils that do not change with changing soil dynamics. Clapp and Hornberger (1978) give representative values for Ψ_S, θ_S and b for each of 11 soil textures, from sand and sandy loam to silt and silty clays, with their values based on experiments. Their power curve representing unsaturated hydraulic conductivity (K) is:

$$K = K_S W^{2b+3} \qquad \text{(Eqn 1.3)}$$

where K_S is the saturated hydraulic conductivity, but is considered a constant property of the soil and does not change with changing soil dynamics. In Table 2 of Clapp and Hornberger (1978), values for K_S are given for a range of 11 textural classes. While SHPs have tended to rely on texture in determining a suitable PTF, a simpler soil hydraulic classification based on a drainage classification may be useful, such as well drained, medium drained, imperfectly drained, and poorly drained. Such a classification may be appropriate if more complex formulations cannot be determined.

1.3.3 Rainfall/Run-off modelling: GEOtop

Rainfall/Run-off models have proved to be a vital tool in many fields and provide solutions to many practical problems, including flood forecasting, assessment of the impacts of effluents on water quality, design of engineered channels, evaluation of flood alleviation schemes, estimation of erosion and loss of OM and much more.

One of the primary drivers for the construction of hydrologic models is the limitation of hydrological measurements, while models provide a means of extrapolating known measurements in both space and time to areas where data are not available (Beven, 2001). A review of the literature reveals a wide range of models, from simple models, such as that based on the unit hydrograph first introduced by Sherman (1932), to complex conceptual distributed catchment models. The original version of GEOtop (Rigon et al., 2006) includes a rigorous treatment of the core hydrological processes (e.g. unsaturated flow, saturated flow, transport surface energy balances and stream flow generation/routing). The energy processes were validated by Bertoldi et al. (2006). A reduction of the latent heat flux was balanced by an increase in the sensible heat flux. Net radiation also showed a minor sensitivity to topography, while the evaporative fraction was shown to be strongly independent of geomorphic characteristics.

2 Materials and Methods

2.1 Background

This project is a study of the interactions of soil hydrology, land use and climate change and their impacts on soil quality. The first task was to determine a hydraulic classification of Irish soils. The second task was to examine the threats to the sustainability of soil quality – erosion, loss of OM, compaction, surface sealing (urbanisation) and landslides – under current and future land use and climate. Threats to soil are primarily dependent on the land's cover type and changes, the land management practices, the topography and climate. The study methodology included the following:

1. A field and laboratory study of soil properties including bulk density, SOC and SHPs, which was used to develop a soil hydraulic classification for Irish soils;
2. An examination of soil erosion: a modelling exercise using the empirical (annual scale) model RUSLE and the process-based model GEOtop (hourly scale);
3. An examination of the loss of soil OM using data from the literature combined with the SEDD model and the process-based model GEOtop using enrichment factors;
4. An examination of soil compaction based on bulk density and the use of GEOtop with a range of density values to determine the impact of compaction on run-off and erosion;
5. An examination of Irish soil surface sealing (urbanisation) in a desk study; and
6. An examination of landslides using GIS to identify areas at risk across Ireland.

2.2 Measurements and Estimation of SHPs

2.2.1 Locations of soil sampling programme

For site selection for field tests, field samples were collected, enabling the determination of the SHPs of a range of soils, representing the land uses and their geographical spread throughout Ireland. As texture (sand, silt and clay (SSC)) is the first measure in understanding SHPs, it was decided that soil texture (rather than soil type) should be a key criterion for the site selection. In order to utilise as many as possible of the existing data from prior soil research projects (e.g. SoilC), the aim was to select as many sites as possible from the 1,310 data points of the National Soil Database (NSD) (Fay and Zhang, 2007; Fay et al., 2007; EPA, 2009) and from the 62 points of the SoilC (Kiely et al., 2010), which are a subset of the NSD sites. From these soil associations, it was possible to estimate the percentage make-up of Irish soils according to the USDA soil textural triangle (Table 2.1). Sites were then selected from the SoilC project to ensure that sites in this study reflected the make-up of Irish soils. As the SoilC project did not include any clay sites, two more sites of clay texture from the NSD were identified and chosen, to bring the total number of sampling sites to 32. The locations of these sites, with details on land use and soil type, are given by Lewis (2011) and in the End of Project Report on SoilH. While the earlier projects (NSD and SoilC) focused on the physical make-up and carbon and mineral contents, in this study (SoilH) the focus also included the SHPs (e.g. hydraulic conductivity $K(\theta)$ and moisture retention characteristics $\Psi(\theta)$). The theory and methods of the site and laboratory experiments are described in more detail in the End of Project Report and in Lewis (2011). Along with the hydraulic properties, samples were taken for standard soil physical properties such as initial and saturated moisture content, particle size analysis and bulk density.

Table 2.1. Distribution of different soil texture classes in Ireland.

Texture classifications	Irish soils (%) (Gardiner and Radford, 1980)	No. of SoilC samples	No. of SoilH samples
Clay	3.7		2
Silty clay	0		
Silty clay loam	3.3	1	1
Sandy clay	0		
Clay loam	17.81	7	7
Medium loam	38.9	18	11
Silty loam	0	1	1
Silt	0		
Sandy clay loam	0.5	1	
Sand	0	1	1
Loamy sand	0		
Sandy loam	17.35	8	8
Total mineral	81.63	37	32
Peat	18.37	21	1
Total	**100**	**58**	**32**

2.2.2 Hydraulic properties, sampling, methods and theory

From a review of both field and laboratory methods for determining hydraulic properties, it was decided that the Beerkan Estimation of Soil Transfer Parameters (BEST) method (Lassabatere et al., 2006; Minasny and McBratney, 2007) was most suited (following earlier discussions with Professor Cuenca of Oregon State University). This method determines both the water retention curve and the hydraulic conductivity curve as defined by their shape and scale parameters. Using the Beerkan field experiment data sets, the BEST algorithm did not result in satisfactory hydraulic properties due to the relatively slow rates of infiltration at a number of sites caused by the high initial moisture content of the Irish soil during the wet summers of 2008 and 2009. Therefore, another algorithm called the Wu method (Wu et al., 1999) was used in these cases.

Field infiltration experiments were carried out at 31 mineral soil sites at three different depths: the surface, 15 cm and 30 cm (Fig. 2.1). These field tests were carried out in accordance with recommendations of

Figure 2.1. Infiltration experiment at Site 180 with the infiltration experiment at surface in the foreground and the infiltration tests 15 and 30 cm below the surface in the trench behind the surface infiltration test. Replicate trenches were dug 2–3 m apart.

Prof. Richard Cuenca of Oregon State University, USA, who provided the field experimental protocol (see Lewis, 2011). Soil samples were also taken for bulk density and moisture content (initial and final) analysis. The initial moisture content of the soil was estimated by taking a soil sample before the infiltration experiment from outside the plastic ring, approximately 30 cm from the infiltration experiment. The final moisture content soil sample was taken from inside the ring after the infiltration experiment was complete and no standing water was remaining on the surface.

2.2.2.1 Field infiltration experiments in mineral soils

After the infiltration experiment, the soil was removed to determine the water penetration depth. Once this had been completed at all three levels, two more trenches were dug 2–3 m to the side of the first trench, and the entire operation was repeated so as to have three replicates for each level. Once the field work (infiltration experiment) had been completed, the cumulative infiltration versus time was plotted, and knowing the pre- and post-experiment soil moisture, the BEST method was used to determine K_{sat}. In the cases where the BEST method did not work due to the slow rate of infiltration (i.e. soil close to or at saturation), the Wu method of analysis (Wu et al., 1999) was used.

2.2.2.2 Bulk density, particle size analysis and moisture content

Bulk density samples were taken at three depths (the surface, 15 cm and 30 cm) using Eijkelkamp ART NR07010253 stainless steel bulking density sampling rings (80 mm diameter by 50 mm high; volume 251 $cm^{3)}$ (Eijkelkamp Agrisearch Equipment BV, The Netherlands). The bulk density samples were taken before the infiltration experiments commenced at a distance of 20–25 cm from the infiltration test locations so as to avoid disturbing the soil around the infiltration test locations. Once the samples were taken, they were sealed and transported to the laboratory, where they were oven-dried at 105°C for 24 h and sieved to 2 mm. Bulk density (ρ) (g/cm^3) was estimated from Eqn 2.1:

$$\rho = M_d / (S_v - CFV) \quad \text{(Eqn 2.1)}$$

where M_d is the dry mass (g) of the sample <2 mm, S_v is the total sample volume (cm^3) and *CFV* is >2 mm coarse fraction volume (cm^3). Material greater than 2 mm was excluded.

2.2.3 Peat soils sampling methods

2.2.3.1 Site description

The Glencar catchment is a pristine Atlantic blanket bog near Glencar in County Kerry, south-west Ireland, (latitude 51° 58' N, longitude 9° 54' W) at an elevation of approximately 150 masl (metres above sea level) and is typical of Atlantic blanket bogs in the coastal regions of north-west Europe (Sottocornola et al., 2009). The depth of the bog varies from ~1.0 m at the margin (e.g. near the stream or road) to over 5 m at the bog interior. The water table is at or near the surface of the peat throughout the year (Sottocornola et al., 2009). A meteorological tower has operated at this site since 2002 and is run by the Hydromet group in University College Cork (UCC) (see http://www.hydromet.org for further details on the tower). The range of annual rainfall since 2002 was 2,236–3,365 mm, with an estimated eddy covariance estimated evapotranspiration range of 369–424 mm and an average of 208 wet days (>1 mm/day) per year. The average annual air temperature is 10.5°C. A small stream runs through the centre of the bog and drains ~76 ha, 85% of which is relatively intact blanket bog.

2.2.3.2 Hydraulic conductivity sampling and laboratory analysis

The mineral soil sampling methods and analysis for mineral soils as previously described are unsuitable for peat soils. Instead, a method described by Beckwith et al. (2003) was used. This involved extracting an undisturbed sample of peat from the field for laboratory analysis. Field work was carried out between November 2009 and January 2010. A total of 14 locations were chosen in a transect running perpendicular to the surface elevation contours from the stream. A timber peg marked each point, and distances between pegs varied from 2.5 m adjacent to the stream to 50 m at the bog interior

2.2.3.3 Bulk density and moisture content site sampling methods and laboratory analysis

Peat samples for bulk density analysis were also taken. Due to the densely rooted nature of near-surface peat, it was not possible to take bulk density samples at or near the surface with conventional bulk density rings. To overcome this problem, bulk density was obtained at the surface using sections of the samples taken for hydraulic conductivity analysis. These samples had a regular shape, which enabled estimates of bulk density. Below 20 cm depth, an Eijkelkamp 04.09 peat sampler (Eijkelkamp, Agrisearch Equipment BV, The Netherlands) for bulk density analysis was used. Using this auger, which has a semicircular shape of diameter 5 cm, the full depth of the peat (in some cases as much as 5 m) was sampled in increments of 0.5 m. These samples were placed in airtight bags for later laboratory analysis. The samples for bulk density (below 50 cm) were oven-dried for 1 week at 55°C. Samples were then weighed and reweighed 24 h later to ensure that all moisture had evaporated. All the samples used in the analysis of hydraulic conductivity were also analysed for bulk density. Once the hydraulic conductivity tests had been completed, the wax was removed from the samples and the length of each side of the cube of peat was measured to determine the volume; the samples were then dried, and bulk density was estimated using Eqn 2.2:

$$\rho_{bd} = m_d / V_{or} = m_d / l \times h \times w \qquad \text{(Eqn 2.2)}$$

where ρ_{bd} is the dry bulk density (g/cm^3), m_d is the dry mass of the sample (g), V_{or} is the original (wet) volume of the peat sample (cm^3), l is the length of the sample (cm), h is the height of the sample (cm) and w is the width of the sample (cm). The conventional gravimetric-based definition of soil moisture (θ_G) as is used for mineral soils is defined as $\theta_G = M_w/M_s$, where M_w is the mass of water in the soil and M_s is the mass of soil. However, given the large proportion of water in peat and the relatively light mass of peat, the conventional definition of gravimetric soil moisture is unsuitable for peat. Peat moisture content was determined using Eqn 2.3:

$$\theta = ((m_{tot} - m_d) / m_{tot}) \times 100 \qquad \text{(Eqn 2.3)}$$

where θ is the mass ratio-based moisture content in %, m_{tot} and m_d are the total wet mass of peat (before drying) and the dry mass of the peat (after drying), respectively. Thus, it was possible to estimate bulk density and moisture content for the entire profile of the peat. Further details are in the End of Project Report and in Lewis (2011).

2.3 Catchment Descriptions for Rainfall/Run-Off Modelling

A number of catchments were considered for examination for rainfall/run-off modelling, soil erosion and loss of organic carbon simulations. These are detailed in Table 2.2.

For rainfall/run-off, erosion and loss of OM analysis, the authors focus on three catchments:

1. The Dripsey grassland;
2. The Glencar peatland; and
3. Three sub-catchments of the Munster Blackwater:
   (i) Duarrigle;
   (ii) Dromcummer; and
   (iii) Mallow.

Table 2.2. Catchment characteristics for catchments.

Sub-catchment	Elevation (m)	Stream length (km)	S1085 (m/km)	Catchment area (km^2)	Land use (%)						Annual rain (mm)
					Grass	Forest	Arable	Peat	Urban	Other	
Dripsey	210–60	8.3	10.3	15	95	2	3	0	0	0	1,470
Glencar	213–141	1.0	22	0.73	10	0	0	90	0	0	2,571
Duarrigle	672–102	20	3.9	245	63.9	15.9	0.6	14.4	0.4	4.5	1,456
Dromcummer	669–67	30	2.7	881	66.1	16.4	4.9	7.5	0.5	2.7	1,356
Mallow	671–35	45	2.1	1278	63.5	14	12.6	5.16	0.9	3.84	1,303

2.4 GEOtop – Rainfall/Run-Off Model

GEOtop (Rigon et al., 2006; Endrizzi et al., 2011) is a distributed hydrological model that simulates the complete hydrological balance in a continuous way during a whole year and is driven by geospatial data (e.g. topography, soil type, vegetation, land cover). It estimates rainfall/run-off and evapotranspiration, and provides spatially distributed outputs, as well as routing water and sediment flows through stream and river networks (Rigon et al., 2006). GEOtop requires a digital elevation model (DEM), land cover data (including crop height, leaf area index, root depth), soil type data (including the vertical and horizontal hydraulic conductivity, θ_r, θ_{wp}, θ_{fc}, θ_s, van Genuchten parameters α and n and the Mualem parameter η) in distributed maps for the catchment. Meteorological data such as precipitation, temperature, incoming short-wave radiation, air pressure, relative humidity, wind speed and direction in hourly time steps from one or more points in or near the catchment are also required. GEOtop outputs all major hydrological properties in hourly time steps. Stream flow is provided at the catchment outfall whereas outputs, such as temperature, soil moisture, depth of water over soil, evaporation from the soil, transpiration from the canopy, water stored in the canopy, water table and snow depth, are all provided in distributed maps suitable for import into a GIS environment.

2.4.1 GEOtop – new soil erosion module

This study focused on impacts to soil resources (and not necessarily on channel integrity): only inter-rill and rill erosion were considered. Therefore only the effects of rain splash detachment and flow detachment were considered. Splash detachment is the detachment of soil particles due to the impact of raindrops on soil, and flow detachment is flow-induced detachment of soil particles from flow forming in small intermittent water gullies or rills over only a few centimetres of depth (see Fig. 2.2) (Boardman and Poesen, 2006).

For the development of the erosion module in GEOtop, the LISEM model (DeRoo et al., 1996) was adopted and a new module was developed in GEOtop for the online calculation of distributed erosion, sediment transport and deposition rates. The LISEM model

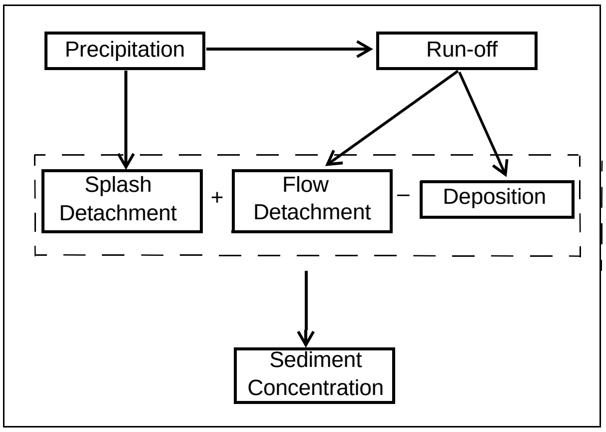

Figure 2.2. Flow chart of erosion processes (from a presentation by J.D. Albertson at the EPA SoilH steering group meeting).

(DeRoo et al., 1996) is a physical-based erosion model that runs at the event and catchment scales. The original LISEM model runs in a GIS environment and modelled erosion comprises splash detachment and flow detachment from overland flow in rills.

2.4.2 GEOtop – new soil organic carbon loss module

The authors have incorporated a SOC loss module into GEOtop, taking advantage of work done on the soil erosion module for GEOtop. The SOC temporal dynamics in a watershed are governed by Eqn 2.4, which considers SOC loss in two separate ways: the particulate organic carbon (POC) loss and leaching of DOC:

$$\mathrm{dSOC} / \mathrm{d}t = litter - R - \mathrm{POC} - \mathrm{DOC} \quad \text{(Eqn 2.4)}$$

$$\mathrm{POC} = SEro \times pocc \times enrichment \quad \text{(Eqn 2.5)}$$

where *SEro* is the rate of soil mass loss due to erosion (g/m^3/day), *pocc* is the concentration of soil particle organic carbon, and *enrichment* is the enrichment factor. The leaching rate of DOC is estimated by Eqn 2.6:

$$\mathrm{DOC} = docc \times q \times A \quad \text{(Eqn 2.6)}$$

where *docc* is dissolved organic carbon concentration in flows (g C/m^3/day), *q* (l/s) is flow rate and *A* is area (m^2). The DOC concentration in flows for each watershed in this study is taken from the DOC values in the SoilC report (Kiely et al., 2010). For each pixel of the watershed, the DOC leaching rate is multiplied by the changes in flow rate within the pixel and the DOC concentration (Zi, 2014).

2.4.3 GEOtop – soil compaction

To examine if any of the soils sampled in this project were compacted, the bulk densities of each site (plus the sites in the EPA SoilC project) based on the % SSC were compared with the actual measured bulk densities. The results are reported in Chapter 3. Functions developed by Assouline (2006a,b) were used. Compaction increases the bulk density and the ratio of compacted to initial bulk density is shown in Eqn 2.7:

$$\rho_c / \rho \geq 1 \qquad \text{(Eqn 2.7)}$$

Assouline (2006a) gives equations for the compacted saturated hydraulic conductivity, and defines the ratio of compacted saturated hydraulic conductivity to initial as Eqn 2.8:

$$K_{sc} / K_s = (\phi_c / \phi)^3 (\rho_c / \rho)^{\delta - 7} \qquad \text{(Eqn 2.8)}$$

where (ϕ_c / ϕ) is the ratio of compacted to initial porosity, and $\delta = 2$ for loamy soils.

In a similar way, the methods for the water retention curve parameters were adopted from Assouline (2006b), modelling the relationship between bulk density and the water retention curve. The two parameters of interest are the van Genuchten α (the inverse of the air entry potential, per cm) and μ (a shape parameter). Assouline (2006b) gives us the following two equations, Eqns 2.9 and 2.10:

$$(\alpha_c / \alpha) = (\rho_c / \rho)^{3.72} \qquad \text{(Eqn 2.9)}$$

$$(\mu_c / \mu) = (\rho_c / \rho)^{\omega} \qquad \text{(Eqn 2.10)}$$

where ω is ~1.0.

2.5 RUSLE and SEDD Models

As noted in Chapter 1, the RUSLE equation is expressed as:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad \text{(Eqn 1.1)}$$

where A is the estimated spatial average soil loss and temporal average soil loss in kg per unit of area, expressed in the units selected for K and for the period selected for R.

To determine the amount of sediment delivered to the stream channel, the erosion amount is multiplied by an SDR from the SEDD model. See End of Project Report and He (2010) for more details.

2.6 Description of Climate Change/Land Use Scenarios

Climate change data are derived from a set of scenarios published by the IPCC in 2001. The IPCC Third Assessment Report (*IPCC Special Report on Emissions Scenarios* – SRES) contained a new set of scenarios which were constructed to explore future developments in the global environment (Nakicenovic et al., 2000). The scenarios cover a wide range of possible futures, and for simplicity are split into four families, A1, A2, B1, B2, with different storylines, each representing different demographic, social, economic, technological and environmental developments. All of these scenarios detail land use change and changes in GHG emissions which have been used by McGrath and Lynch (2008) for predicting changes to the future climate in Ireland. The storylines of the four scenarios are summarised in Nakicenovic et al. (2000). Tables 2.3 and 2.4 present, respectively, the climate change and land use scenario examined in this project. The future scenario simulations are based on the SRES A1B Scenario (Nakicenovic et al. (2000) and the generalised results from the Community Climate Change Consortium for Ireland (C4i) (McGrath and Lynch, 2008)). The percentage differences are from the current baseline of the 1961–2000 record.

Table 2.3. Climate change scenario (2021–2060).

Month	January–April	May–August	September–December
Rainfall	+15%	–10%	+15%
Temperature	+1.25°C	+1.25°C	+1.25°C

Table 2.4. Land use change (LUC) scenarios.

Scenario no.	LUC-1	LUC-2
All catchments	+10% forestry	+20% forestry

3 Summary Results of Experiments of Field Soils

3.1 Introduction

To examine the threats to Irish soils, a modelling capability to extend point information to the scale of the catchment is required. The development to the rainfall/run-off model – GEOtop – in this study enables point and catchment-scale data to be used as input to examine time series (e.g. increments of 1 h) catchment-scale outputs of erosion and loss of OM and compaction. The combination of GIS (and catchment-scale data products, e.g. topography) and the empirical erosion models – RUSLE and SEDD – enables *annual* scale erosion and sediment delivery at the catchment and national scales to be estimated. GIS techniques are exploited to examine surface sealing (urbanisation/ suburbanisation) and landslides using available data products from the EPA, GSI and others. The soil properties thus quantified are:

1. Land cover
2. Soil type (great soil group, e.g. brown podsols)
3. Physical properties
   - % sand, % silt, % clay (% SSC)
   - Bulk density
   - Porosity
   - USDA soil triangle classification (loam, etc.)
   - Gradation (poorly graded, well graded)
4. Chemical properties
   - SOC (%)
5. Hydraulic properties
   - Hydraulic conductivity (unsaturated and saturated)
   - Soil water retention characteristics (scale and shape parameters).

3.2 Mineral Soils

Soil samples were analysed for physical, chemical and hydraulic properties, including bulk density, particle size distribution, shape and scale parameters for water retention and hydraulic conductivity characteristics. The results from all samples are compiled in detail in the End of Project Report.

3.2.1 *Mineral soil type*

Of all the samples taken, the soil type (from great soil groups), soil classification (as per the USDA triangle), land cover (pasture, etc.), county and co-ordinates are presented in Table 2.2 of the End of Project Report. From Table 2.1 (this report), it can be noted that, from the Gardiner and Radford (1980) classification and in the soil sample set used in this study, the three most abundant mineral soil classifications in Ireland are all loams: medium loam, clay loam and sandy loam. Loam is a soil composed of sand, silt and clay in relatively even concentration, with clay typically being the lowest fraction (about 40%–40%–20% concentration of sand, silt and clay).

Loam is considered ideal for agricultural uses because it retains nutrients well and retains water while still allowing excess water to drain away.

3.2.2 *Soil classification – USDA*

The 31 mineral soil locations were sampled for three replicates and at three depths (the surface, at 15 cm and at 30 cm). In total, 279 unique soil samples were analysed. The USDA classification of the 279 samples is shown in the USDA soil classification triangle (Fig. 3.1). Most of the samples in this study line up in the medium loam location, with many others in the sandy end of the triangle. The two clay samples (with clay content ~45%) were the only clay samples. It is of interest to note that there are no ‘silt’ or silty loam samples (as was the case with Gardiner and Radford, 1980).

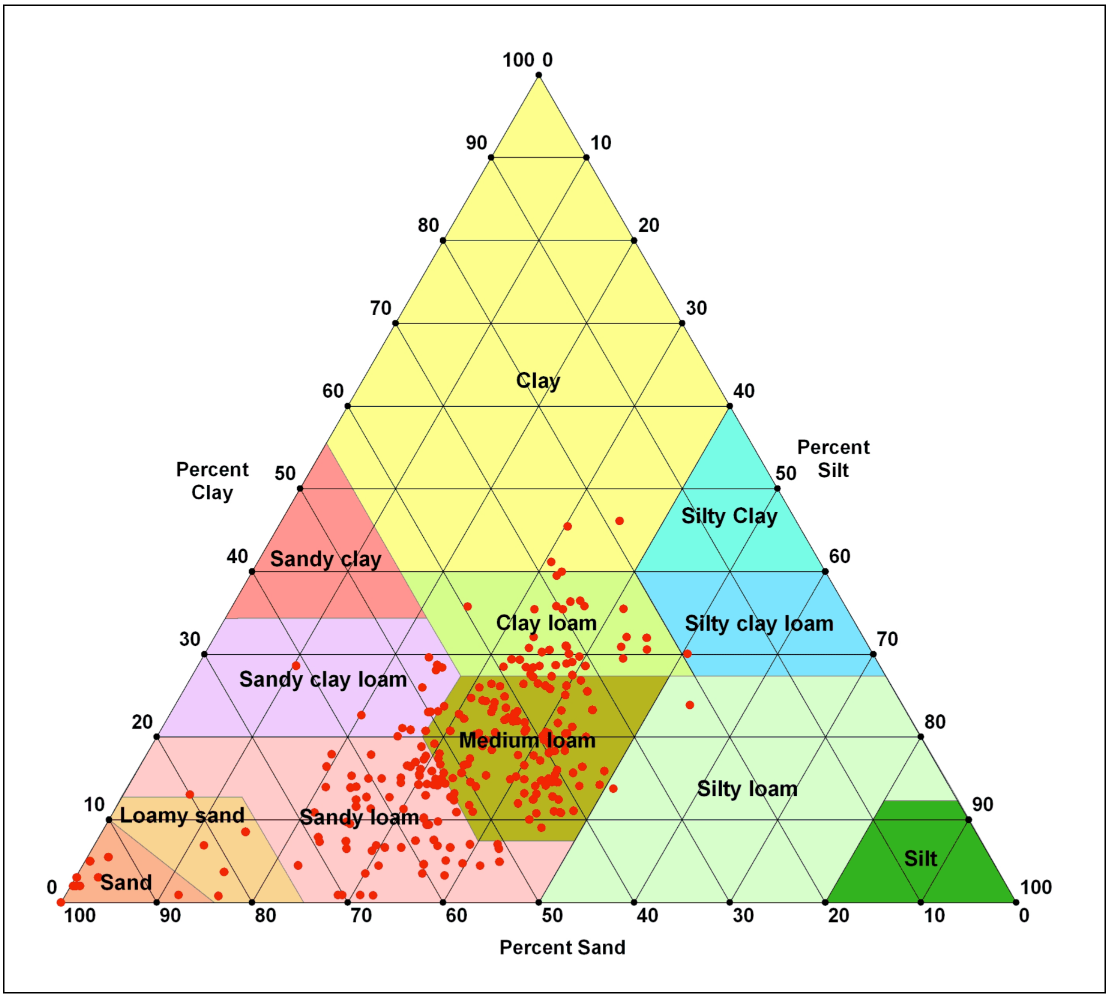

Figure 3.1. Particle size distributions for 31 mineral sites on the United States Department of Agriculture (USDA) soil classification triangle. The concentration of sites is in the medium–sandy loam region.

3.2.3 Bulk density and porosity of mineral soils

The bulk density and porosity of the mineral soil samples are included in Table 3.4 of the End of Project Report. Bulk density is a dynamic property that changes with the degree of compaction (or land use) and is therefore an indicator of 'soil compaction'. The fine soil (<2 mm) bulk density is defined as the dry weight divided by its volume, expressed in g/cm^3. Bulk density is dependent on soil texture, % SSC, the SOC and the soil packing. Assuming that most rocks have a bulk density of 2.65 g/cm^3, a medium textured soil with 50% porosity has a bulk density of ~1.33 g/cm^3. Loose and porous soils and those with high SOC have lower bulk densities, while sandy (and compacted) soils have higher densities than 1.33 g/cm^3. Sandy soils have higher densities attributed to the lack of macropores. Fine-textured soils, such as silt and clay loams that have good structure, have higher pore space (and possibly macropores), resulting in lower bulk density. Bulk density generally increases with depth, as the lower depths have lower SOC, less root penetration and less pore space, and are sometimes subject to greater compaction than the surface layers. Porosity is normally calculated from Eqn 3.1:

$$\phi = 1 - (\rho_{bulk} / \rho_{particle}) \qquad \text{(Eqn 3.1)}$$

3.2.4 Gradation of mineral soils

Soil gradation is a classification that ranks the soil based on the different particle sizes contained in it. Soil gradation is an indicator of potential compressibility, shear strength and hydraulic conductivity. The gradation of the in-situ soil often controls the groundwater drainage of the site. Soil is graded as either well graded or poorly graded. A well-graded soil contains fractions across the range of clay, silt and sand. A poorly graded soil will have better drainage than a well-graded soil. The majority of the soils sampled in this project were well graded, and it is significant that such well-graded soils generally have poor infiltration characteristics and low hydraulic conductivities.

3.2.5 Hydraulic properties of mineral soils

Figure 3.2 shows the water retention shape parameter *n*, volumetric saturated soil moisture (θ_S), the saturated hydraulic conductivity (K_S) and van Genuchten water retention parameter (α) partitioned into eight of the 12 classes as defined by the USDA soil texture triangle. Saturated volumetric soil moisture is lowest in sand, with values ranging from 0.35 to 0.4 (cm^3/cm^3), and a mean value of ~0.38.

These values are very similar to those of Schaap and Leij (2000) and Clapp and Hornberger (1978). For the soil water retention shape parameter *n* (a measure of the pore size distribution), the sand class is significantly different from all other texture classes. All classes shown in Fig. 3.2 show the study *n* value ~2.0 except for sand, which has an *n* value of >3. The *n* values from Schaap and Leij (2000) are all ~1.3 except for sand, which has an *n* value of ~3.

Kutilek and Nielsen (1994) note that *n* ranges between 1 and 4. As *n* is a measure of the pore size distribution, it may also be considered some measure of 'grading'. For the second soil water retention fitting parameter, α, the study results are ~0.1/cm while those of Schaap and Leij (2000) are closer to 0.01/cm and Kutilek and Nielsen (1994) note a range of 0.01–0.001/cm. α is considered as a measure of the inverse of the air entry potential (at saturation), per cm. The highest van Genuchten water retention parameter (α) is for sand with a value close to 1. This is an order of magnitude higher than that of Schaap and Leij (2000).

The saturated hydraulic conductivity is highest in sandy soils, while it is lowest in clay soils. The differences in saturated hydraulic conductivity between soils of different texture vary by over three orders of magnitude. For clays, the study K_S values are

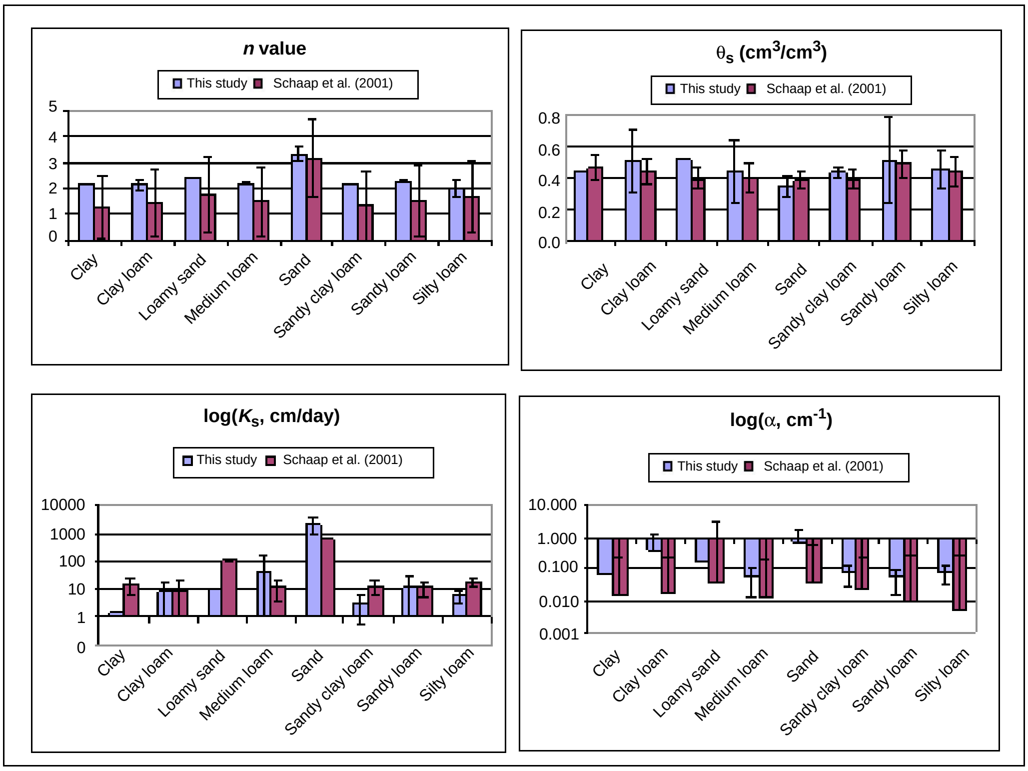

Figure 3.2. Soil hydraulic properties by texture: results from this study versus those of Schaap and Leij (2000).

~2 cm/day, compared with those of Clapp and Hornberger (1978) of ~25 cm/day and Schaap and Leij (2000) of ~20 cm/day. For medium loams (where most of the study soil samples are concentrated), the K_s values are ~30 cm/day, compared with those of Clapp and Hornberger's (1978) of ~60 cm/day and Schaap and Leij's (2000) of ~110 cm/day. For sands, the study K_s values are ~2,000 cm/day, compared with those of Clapp and Hornberger (1978) of ~1,500 cm/day and Schaap and Leij's (2000) of ~180 cm/day. The study values are somewhat different from the well-known separate data sets presented by Schaap and Leij (2000) and Clapp and Hornberger (1978). This may reflect the fact that SHPs have high spatial variation in nature, and different methods often produce high difference in values of same-SHPs. The authors also find that the sand class seems very different in soil physical and hydraulic properties from other texture classes (for the study data set and that of Schaap and Leij, 2000), and therefore *using the texture classes may not be an optimum hydraulic classification system for Irish soils.*

3.3 Peat Soils – Bulk Density and Saturated Hydraulic Conductivity

In the detailed field study at the pristine blanket peatland at Glencar in County Kerry, the authors present results on two key variables: bulk density (ρ_{bd}), and saturated hydraulic conductivity (K_{sat}).

3.3.1 Peat soils – bulk density

There is a wide range of bulk density values identified in peatlands worldwide, from lows of ~0.06 g/cm^3 to highs of 0.79 g/cm^3. The lower values are in well-decomposed peats, while the higher values are likely to be a mixture of peats and mineral soils or shallow peats. The authors found that the bulk density at Glencar decreased with increasing distance from the boundaries (e.g. stream). At the interior of the bog, the bulk density was 0.055 g/cm^3 and this varied little with depth. At the stream edge (bog margin), the peat depth was <1 m and increased to >5 m at the bog centre. At the time of sampling (wintertime), the water table depth at the margin was ~10 cm below the surface and was at the surface near the bog interior. A summary of the study measured bulk density (ρ_{bd}) results shows a range from 0.038 to 0.165 g/cm^3. Near the stream margin, the depth averaged bulk density was highest at ~0.11 g/cm^3. The bulk density values reported here are similar to those of Wellock et al. (2011b), Tomlinson and Davidson (2000) and others for peatlands with depths greater than 2 m (see Table 3.2 in the End of Project Report).

3.3.2 Peat soils – saturated hydraulic conductivity

Both the K_{hsat} (horizontal) and K_{vsat} (vertical) at the near surface and sub-surface showed a significant increase between the riparian zone and the centre bog zone. K_{hsat} for the near-surface depth (10–20 cm) ranged from ~10^{-7} m/s near the stream to ~10^{-4} m/s at the bog interior, a difference of three orders of magnitude. K_{vsat} for the near-surface depth ranged from ~10^{-6} m/s near the stream to ~10^{-4} m/s at the bog centre. K_{hsat} for the sub-surface depth (30–40 cm) ranged from ~10^{-6} m/s near the stream to ~10^{-4} m/s at the bog centre. K_{vsat} for the sub-surface depth ranged from ~10^{-6} m/s near the stream to ~10^{-5} m/s at the bog centre. The authors found that anisotropy does exist, with horizontal hydraulic conductivity approximately twice that of the vertical hydraulic conductivity. The values of saturated hydraulic conductivity found in this study compare with those of others, including Beckwith et al. (2003), who used the modified cube method in Thorne Moors, UK (raised bog), which was also used in this study, and found that the vertical hydraulic conductivity near the surface ranged from 10^{-3} to 1.6 × 10^{-5} m/s and horizontal hydraulic conductivity ranged from 8 ×10^{-4} to 1.6 × 10^{-5} m/s. Beckwith et al. (2003) also reported vertical conductivity values at depths of 30 cm that ranged from 3.2 × 10^{-7} to 7.9 × 10^{-7} m/s and horizontal conductivity values at the same location that ranged from 2.5 × 10^{-6} to 10^{-5} m/s. With K_{hsat} about twice that of K_{vsat} for the near surface, this suggests that at the bog interior the tendency is for rainfall excess to become (horizontal) flow rather than vertical flow. Studies by Reeve et al. (2000) also suggest that when a peat forms over a low-permeability soil, such as exists in Glencar with its clay base, the vertical movement of water through the bog profile is negligible and lateral flow dominates. As the water table at Glencar is close to the surface all the year round (especially at the bog interior), the bog profile is saturated from below and undergoes saturated excess overland flow (SEOF). The authors also suggest that due to the inability of water to resist shear force, peat with high moisture contents will have less structural stability and may be more at risk of peat movement and slides. Creighton (2006) documented such failures in Irish blanket peatlands. The nature of the topography of the peatland in Glencar is such that shallower peat depths occur at lower elevations adjacent to the stream and greater depths at higher elevations were found in the bog interior. This leads the authors to suggest that the peat in the riparian zone, which has a lower moisture content and a higher bulk density, structurally supports the less dense peat of the interior of the bog.

3.4 Compaction

To investigate if there was evidence of compaction of Irish soils, the 46 mineral soil sites of the EPA SoilC project were examined. The sites from SoilC were used, as bulk density to a depth of 50 cm was available, while that of the current SoilH project examined the soil profile to a depth of 30 cm. The bulk density data for three depths is presented: 0–10 cm, 10–25 cm, and 25–50 cm. In Table 3.5 of the End of Project Report, two columns of bulk density are presented: the first (Column 8) is the bulk density determined by the gravimetric methods used in the study; the second (Column 9) is the bulk density estimated from the textural analysis. The latter is estimated based on the methods described in http://www.pedosphere.ca and in Saxton et al. (1986). Comparing the gravimetric (*actual*) bulk densities of Columns 8 and 9 (*estimated from textural analysis*), it can be noted that the measured gravimetric bulk density is frequently less than the textural analysis estimate. This suggests that, in most sites examined, there is little compaction. The authors consider that this is due to the loose porous nature of Irish mineral topsoils, which are rich in OM (>3% SOC) and are perennially well watered. These factors militate against compaction. However, there may be issues with the way bulk density is measured. It is standard practice to exclude >2-mm size particles when bulk density is required in determining soil carbon stocks. It may be appropriate to measure bulk density twice: once excluding >2-mm size particles, and once including the >2-mm size particles. It would be relevant to determine if the bulk densities in the two methods of measurement are different for a range of Irish soils and Irish land uses.

4 Hydrological Classification of Irish Soils

4.1 Background

In many countries, there is a wealth of data on soil physical, chemical and biological properties. Some of these properties are a function of soil type or texture. In other words, they may not change from region to region and are sometimes considered to be constant. However, many soil properties are not constant but dynamic, responding to external influences of climate, land use or land use change. We can use textural analysis (% SSC) as a preliminary guide to determine (say) bulk density, noting that external influences such as precipitation, climate, land use and land use change also can impact the bulk density magnitude. If the physical, chemical and biological properties can change over time, it can be assumed that the hydraulic properties can also change. The two key hydraulic properties of interest are *hydraulic conductivity* and *soil water retention*. Determining the hydraulic properties is not a simple process and is time consuming, with extensive field and laboratory work required. Thus, much effort has been applied in developing mathematical and statistical relationships between conventional soils data (e.g. texture) and SHPs. These relationships are called *pedotransfer functions* (PTFs), which emphasise the link between soil survey ('pedology') and soil hydrology (Pachepsky and Rawls, 2004). In modelling work (e.g. rainfall/run-off), modelling-related SHPs are required. Statistical regression is the traditional tool of PTFs, but artificial neural networks (ANNs) are now proving attractive because of their ability to model complex systems and to exploit data sets into 'training' and 'validation' sets. Particle size distribution and its parameters are used in many PTFs. The non-linearity in SHPs creates difficulties in PTF estimation. As SOC and composition affect both soil structure and adsorption properties, and therefore bulk density, water retention and hydraulic conductivity may be affected by SOC.

4.2 Mineral Site Sampling

Infiltration tests were carried out on the 31 mineral sites over the summer months of 2008 and 2009, taking 8–10 h for each site to be completed. It was not easy to satisfy the requirement to have an unsaturated soil at the start of the experiment, as these two summers were unusually wet. A full description of all the infiltration tests at all the sites, and results, can be found in Lewis (2011).

4.2.1 *Particle size distribution, porosity and bulk density*

The results of the particle size distribution (PSD) analysis and bulk density are presented in the End of Project Report, with Figure 3 there containing a summary of the results from the PSD analysis. Medium loams and sandy loams accounted for a high proportion of the soils analysed. This is to be expected given that between them, medium-loam and sandy-loam soils account for over 56% of Irish soils.

4.2.2 *Mineral sites infiltration results*

From the infiltration experiments, K_S, θ_S and the van Genuchten (1980) parameters α, *m* and *n* were estimated for all sites. These van Genuchten parameters are used to establish the water retention curve. The results of each infiltration experiment are given in Lewis (2011).

4.3 Hydraulic Classification of Irish Soils

Two possible hydraulic classification schemes were examined in this study.

The first scheme was based on the 44 soil profiles from Gardiner and Radford (1980). For each profile, the % SSC, SOC, and the spatial distribution map were used, and PTFs were created to map the existing *soil properties* (e.g. SSC) to *new hydrological soil properties* (e.g. soil water retention shape parameter (*n*), soil porosity (ϕ), K_S, and van Genuchten water retention parameter (α)). From the data set, a robust function to estimate bulk density from SOC (Fig. 4.1a) and Eqn 4.1 was developed.

$$BD = 1.39 - 0.312 \mathrm{Ln}(\%SOC) \qquad \text{(Eqn 4.1)}$$

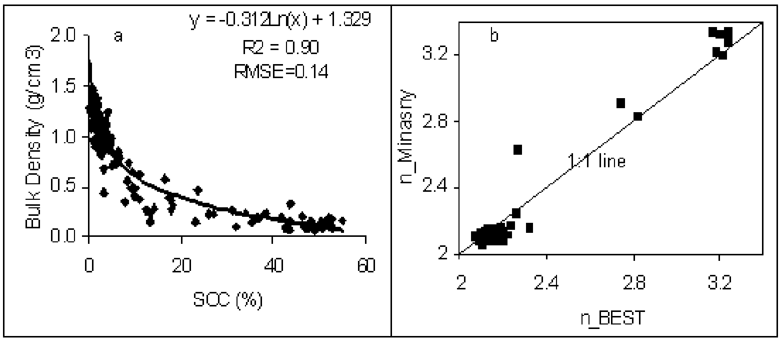

Figure 4.1. Relationships (a) between bulk density and soil organic carbon (SOC), and (b) between the Minasny estimated *n* and Beerkan Estimation of Soil Transfer (BEST) estimated *n*. RMSE, root mean square error.

Based on the SoilH database, the authors found that Eqn 4.2 estimates the water retention shape parameter *n*, developed by Minasny and McBratney (2007), and can be applied to Irish soils (Fig. 4.1b). Clay and sand content are the only two inputs required. The Minasny model is defined as:

$$n = 2.18 + 0.11[48.087 - (44.954 / 1 + \exp(-x_1)) - (1.023 / 1 + \exp(-x_2)) - (3.896 / 1 + \exp(-x_3))] \quad \text{(Eqn 4.2)}$$

$$x_1 = 24.547 - 0.238\,sand - 0.082\,clay \quad \text{(Eqn 4.2a)}$$

$$x_2 = 3.569 + 0.081\,sand \quad \text{(Eqn 4.2b)}$$

$$x_3 = 0.694 - 0.024\,sand + 0.048\,clay \quad \text{(Eqn 4.2c)}$$

The *sand* and *clay* refer to sand and clay content (%). Although many methods were tried (e.g. ANN models and multiple regression methods), the authors were unable to identify a robust relationship between the hydraulic properties (K_s and α) and their measured readily available soil properties (% SSC, soil particle size distribution, soil carbon content, bulk density). This suggests the limitation of field testing in wet weather and possibly some uniqueness of Irish soils.

The second scheme (Fig. 4.2) is based on the existing Irish Forest Service (IFS) soil database. There are some hydrological classifications in the IFS database (e.g. deep, well-drained mineral), therefore some of the existing IFS classes were calibrated and adjusted with the study database (SoilH).

4.4 IFS Hydrological Classification of Irish Soils

4.4.1 Irish soil surveys and the IFS

As no satisfactory relationship was found between the SHPs (K_s and α) and readily measurable soil properties (% SSC), the second classification scheme (Fig. 4.2) was examined. The IFS soil database from the EPA (produced from the project of soils and

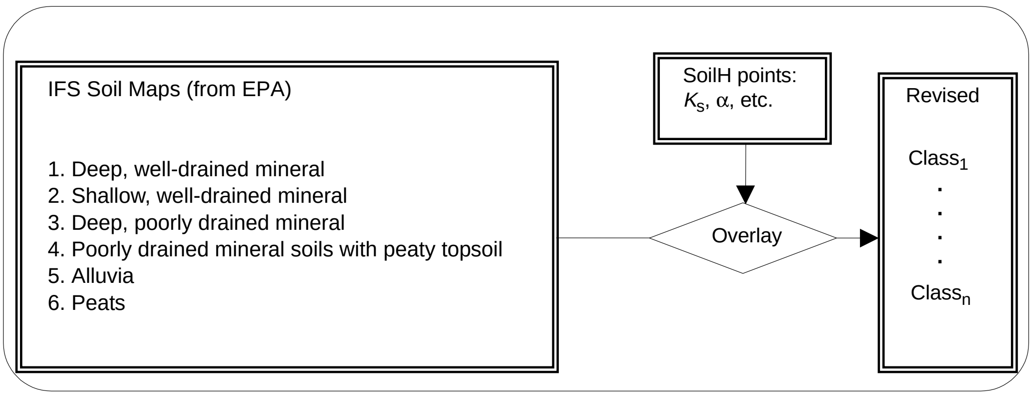

Figure 4.2. Irish Forest Service (IFS) scheme for soil hydrological classification.

subsoils data generated by Teagasc with co-operation of the IFS, the EPA and the GSI, completed May 2006) has seven classes (Table 4.1), with spatial distribution shown in Fig. 4.3. The soil types being modelled fall into seven broad classes. In order to build a national classification of hydraulic properties of Irish soils, the results of the estimates of the hydraulic parameters from the study's 31 mineral sites were compared with the soil groups of the IFS soil database. From the 31 mineral sites with infiltration experiments, 16 sites are in the first category of the IFS soil class (deep, well-drained mineral), which represents 31.1% of Irish soils. The selected sites included only one site in the second category (shallow, well-drained mineral), representing 9.31% of the country. Twelve sites are in the third category (deep, poorly drained mineral), representing 20.36% of Irish soils. The fourth category (poorly drained mineral soils with peaty topsoil) and the fifth category (alluvia), each representing just over 3%, include one site each.

Table 4.1. Irish Forest Service (IFS) soil classes and national coverage.

Soil class (IFS soil class)	Class code	Irish soils (%)
Deep, well-drained mineral	1	31.1
Shallow, well-drained mineral	2	9.31
Deep, poorly drained mineral	3	20.36
Poorly drained mineral soils with peaty topsoil	4	3.3
Alluvia	5	3.55
Peats	6	29.1
Miscellaneous	7	3.28

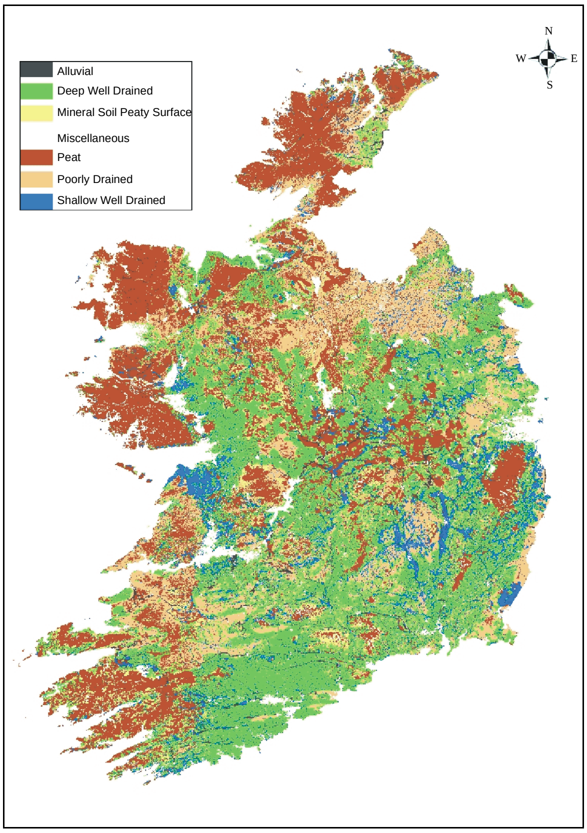

Figure 4.3. Distribution across Ireland of the Irish Forest Service (IFS) soil classes.

Table 4.2 shows that the IFS soil database captures the difference in the K_S and steady infiltration rate between well-drained and poorly drained classes. Deep, well-drained mineral soils have the highest K_S (average 19.29 m/s × 10^{-6}, max. 249 m/s × 10^{-6}, min. 0.35 m/s × 10^{-6}), with the K_S of poorly drained mineral sites being two orders of magnitude lower (average 0.89 m/s × 10^{-6}, max. 2.4 m/s × 10^{-6}, min. 0.24 m/s × 10^{-6}). Excluding the peat soils and alluvium, estimates of θ_S were between 0.36 and 0.46 (l/l). The highest values of the van Genuchten (1980) parameter α were observed (0.16/cm) in deep, well-drained mineral soils, with the lowest α in deep, poorly drained mineral soils (0.06/cm). The van Genuchten (1980) parameter *n* ranged from 1.99 to 2.28.

4.5 Hydrological Classification of Irish Soils – Summary

As the existing classification in the IFS soil database is able to capture the differences in the saturated hydraulic conductivity (K_{sat}) and steady-state infiltration rate between well-drained and poorly drained classes (Fig. 4.4), the authors propose to retain this IFS classification. It is important to note that the *existing* IFS *qualitative* classes CANNOT be used for hydrological models. These classes are therefore *quantified* (see Table 4.2), based on the available data sets of hydraulic properties from this project (SoilH). This updated quantitative information on SHPs for these classes can NOW be used in hydrological models (e.g. GEOtop).

Table 4.2. Soil hydrological properties for Irish Forest Service (IFS) soil classes.

Soil class (IFS soil class)	Class code	Number of SoilH sites	*n* Water retention parameter	θ_S (vol/vol)	K_S (cm/day)	α (per cm)	q_S (cm/day)
Deep, well-drained mineral	1	16	2.28 ± 0.28	0.46 ± 0.17	166.6 ± 534.4	0.16 ± 0.029	1,017.9 ± 2,712.6
Shallow, well-drained mineral	2	1	2.25	0.36	22.2	0.02	360.0
Deep, poorly drained mineral	3	12	1.99 ± 0.65	0.42 ± 0.18	7.8 ± 6.8	0.06 ± 0.04	54.6 ± 77.7
Poorly drained mineral soils with peaty topsoil	4	1	2.16	0.63	3.1	0.11	6.8
Alluvia	5	1	2.16	0.75	14.2	0.09	54.4
Peats	6	1 bog centre 1 bog edge	–	–	1,030 1.03	–	–
Miscellaneous	7	0					

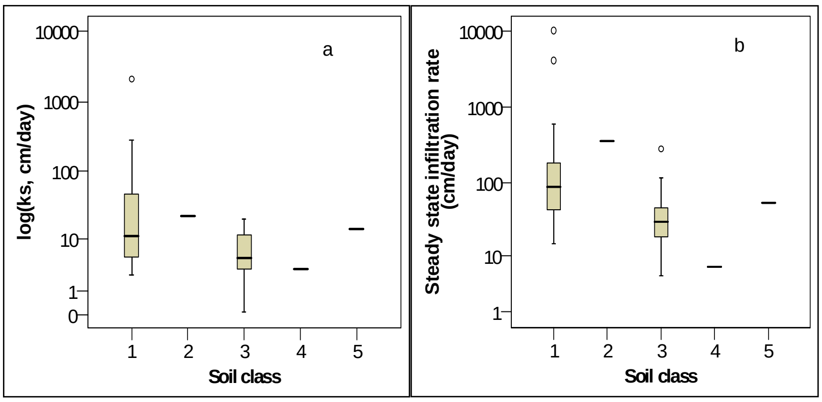

Figure 4.4. (a) Saturated hydraulic conductivity, and (b) steady-state infiltration rate for each new SoilH class.

5 GEOtop Results

The GEOtop process-based rainfall/run-off model, with the new code for erosion and loss of OM, was run in two modes – *calibration* and *validation* – for each of five catchments. Rainfall, radiation and all the meteorological data were input with topography, and the spatial distribution of soils and land cover at a pixel size of ~100 m by 100 m. For each catchment, the authors used a time series of observed river flow at 30-min intervals for a number of years. The GEOtop was run for 1 year in *calibration mode*, *calibrating* some of the parameters that were not known to the authors (i.e. soil hydrological parameters, including hydraulic conductivity). Once the model gave satisfactory results for stream flow (and water balance), the calibrated parameter set was accepted. The model was then run in *validation mode*, with a different year of input data and without changing any of the prior calibrated parameters. The measure of how well the model performs is how well the modelled river flow compares with the observed times series flow during validation.

5.1 GEOtop – Dripsey Catchment

For the 15-km^2 Dripsey grassland catchment, the year 2002 was used to calibrate and 2003 for validation. During the calibration process, parameters such as hydraulic conductivity, leaf area index, root depth and the van Genuchten (1980) parameters, α and n were varied to give the closest fit of simulated river flow to observed flow.

5.1.1 GEOtop – Dripsey – calibration, validation and SSY

GEOtop was validated using the observed river flow data for 2003 and the optimised parameters set from the calibration exercise of 2002. Figure 5.1 shows the observed and simulated flows for the validation year 2003. The rainfall for 2003 was 1,198 mm. The simulated and observed annual flows were 774 mm and 695 mm, respectively. The estimate of evapotranspiration was 503 mm.

The results of the simulated and the observed SSY are presented in Fig. 5.2 for the validation year 2003. It is relevant to note that the flow proportional sampling of suspended solids covered 42% of the 2002 year. For 2002, the simulated SSY was 0.159 t/ha, while the observed SSY was slightly lower at 0.136 t/ha. Most sediment is delivered to the stream in the high-flow months of winter. As the modelled SSY was higher than the observed, the modelled may possibly be more

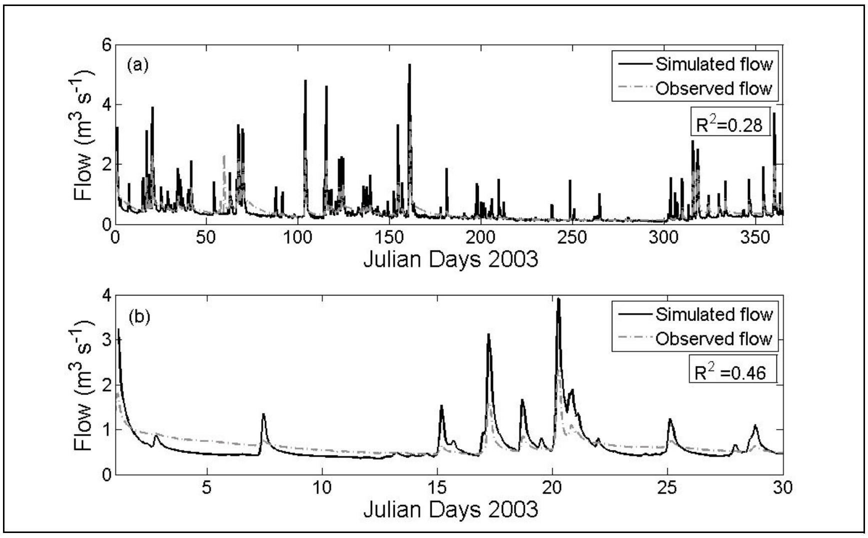

Figure 5.1. (a) Observed and simulated flows for the validation year 2003, and (b) observed and simulated flows for the first 30 days of 2003, for the Dripsey.

accurate, as the observed were sampled for only 42% of the year, and the measured may have missed pulses during non-sampling periods. Figure 5.2 presents the SSY results for the validation year 2003. The model estimates of SSY at 0.053 t/ha were lower than the observed SSY of 0.092 t/ha. It is relevant to note that the flow proportional sampling of suspended solids covered only 21% of 2003 or half the frequency of 2002. Furthermore, 2003 had only 774 mm of stream flow by comparison with 1,268 mm in 2002. Hence, it is likely that the 'observed' SSY might have been overestimated in the gap-filling method due to the lower frequency of suspended solids measurements.

Figure 5.2b shows the simulated moisture content ranging from 23% to 39%. The minimum moisture never dropped below the wilting point (21%), while the soil remained saturated for 57.8% of 2002 and 38.3% of 2003. July–September tended to have lower soil moisture for both 2002 and 2003, while, for November–April, the moisture content remained close to or at saturation. Figure 5.2b shows that the months with higher SSY correspond to the months where the soil moisture is close to saturation. It is noted (in tables in the End of Project Report) that 2002 had rainfall of 1,822 mm and 2003 had rainfall of 1,180 mm. The observed flow and SSY responses were different in the two contrasting years. GEOtop simulates the flow and the SSY reasonably well.

The summer months have almost no SSY, while the winter months have higher erosion and sediment yield. The SSY modelled in both years ranges from 53 to 159 kg C/ha/year. Assuming an SDR factor of 0.4, then the erosion ranges from 159 to 397 kg C/ha/year. Assuming an enrichment factor of 3.5%, the SOC lost ranged from 6 to 14 kg C/ha/year or was of the order of 10 kg C/ha/year.

5.1.2 *Dripsey – GEOtop compaction modelling study*

Table 5.1 presents the results of the GEOtop compaction modelling scenario for the 15-km^2 Dripsey grassland catchment. Three cases are shown:

1. No compaction;

2. Increase bulk density by 10%; decrease saturated hydraulic conductivity by 50% and altered water retention curve parameters as per Assouline (2006a, 2006b); and

3. Increase bulk density by 20%, decrease saturated hydraulic conductivity by 80% and altered water retention curve parameters according to Assouline (2006a,b).

For the modelling exercise, the rainfall (year 2006) was kept the same as in the 'no compaction' case. The first result is that the annual overall flows show little change. The instantaneous flows reach higher peaks with increasing compaction (see Table 5.1 and Fig. 5.3). The major result is that with increasing compaction, erosion does increase, as does the loss of

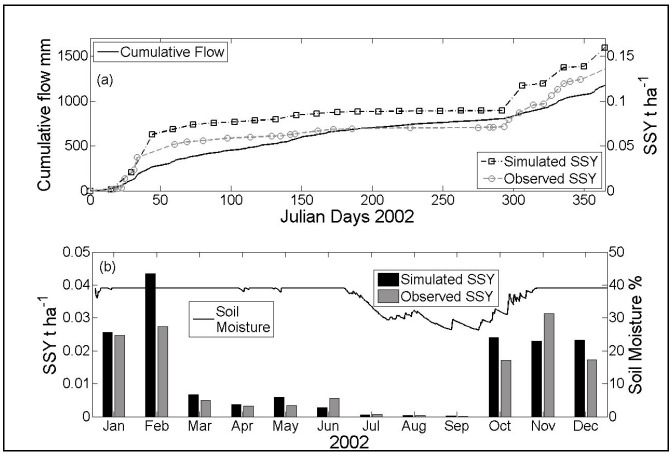

Figure 5.2. (a) Observed and simulated SSY for the validation year 2003, and (b) monthly totals of simulated suspended solids yield (SSY), observed SSY and catchment average soil moisture content, for the Dripsey.

Table 5.1. GEOtop modelling study of compaction at the Dripsey for the year 2006.

Month	No compaction				10% compaction				20% compaction			
	Rain (mm)	Flow (mm)	Erosion (t/ha)	SOC (t C/ha)	Rain (mm)	Flow (mm)	Erosion (t/ha)	SOC (t C/ha)	Rain (mm)	Flow (mm)	Erosion (t/ha)	SOC (t C/ha)
January	286.5	151.4	0.025	0.0079	286.47	138.23	0.0704	0.0088	286.47	132.47	0.201	0.0096
February	114.9	188	0.041	0.011	114.87	182.51	0.1348	0.0125	114.87	180.63	0.279	0.0135
March	237.1	92.7	0.007	0.004	237.11	76.429	0.0156	0.0042	237.11	64.047	0.044	0.0042
April	129	78	0.0036	0.0029	129	73.902	0.0088	0.0038	129	71.571	0.025	0.0047
May	164.8	97.5	0.0059	0.0039	164.8	101.81	0.0182	0.0058	164.8	104.98	0.055	0.0072
June	19.2	69.4	0.0028	0.0023	19.2	57.284	0.0080	0.0027	19.2	47.173	0.027	0.0029
July	52.9	41.5	0.0005	0.0009	52.85	29.346	0.0007	0.0009	52.85	14.959	0.001	0.0005
August	41.5	38	0.0005	0.0007	41.525	33.397	0.0010	0.0010	41.525	22.013	0.001	0.0009
September	214.2	25.7	0.0002	0.00035	214.22	24.054	0.0004	0.0006	214.22	14.95	0.001	0.0005
October	173	76.1	0.017	0.0026	173	107.42	0.0495	0.0055	173	137.58	0.145	0.0091
November	132.13	164	0.024	0.0082	132.13	184.27	0.0622	0.0118	132.13	206.97	0.252	0.0153
December	258	162.8	0.0247	0.0087	258	160.93	0.0602	0.0105	258	163.04	0.214	0.0120
SUM	**1,823.2**	**1,185.4**	**0.152**	**0.054**	**1,823.1**	**1,169.5**	**0.4304**	**0.0685**	**1,823.1**	**1,160.3**	**1.248**	**0.0808**

SOC, Soil organic carbon.

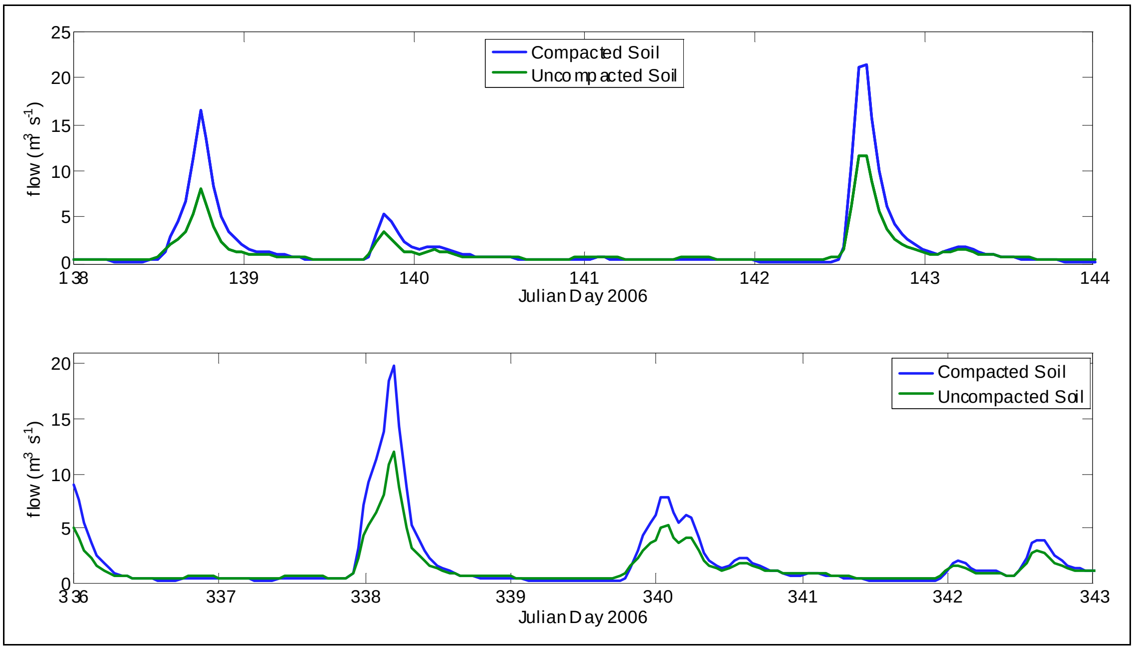

Figure 5.3. GEOtop simulations of compaction on river run-off for the 15-km^2 Dripsey catchment for periods of 2006. The green line represents the time series of flow for the uncompacted (or as is) conditions. The blue line represents the compacted conditions based on a 20% increase in bulk density and an 80% decrease in hydraulic conductivity.

SOC. This verifies the usefulness of GEOtop for modelling flow, erosion and SSY.

5.2 GEOtop – Glencar Peatland Catchment

For this peatland catchment, this study's interests are in stream flow and DOC export. The same methodology was used with GEOtop as with the Dripsey catchment. The data for 2007 were used as the calibration year and 2008 as the validation year. The time series of observed and modelled flows are shown for the validation year 2008 (Figs 5.4 and 5.5) and the model is seen to perform reasonably well. Table 5.2 summarises the results of GEOtop for 2007 and 2008. It is interesting to note that the run-off/rainfall ratio is >75% and increases as the years get wetter. It is interesting that the modelled flow results in the validation year 2008 are as good as the calibration year 2007, with similar R^2. Figure 5.6 shows the time series of observed and modelled water table. Again, the model results are very satisfactory, with the model being within a few centimetres of the observations. It is

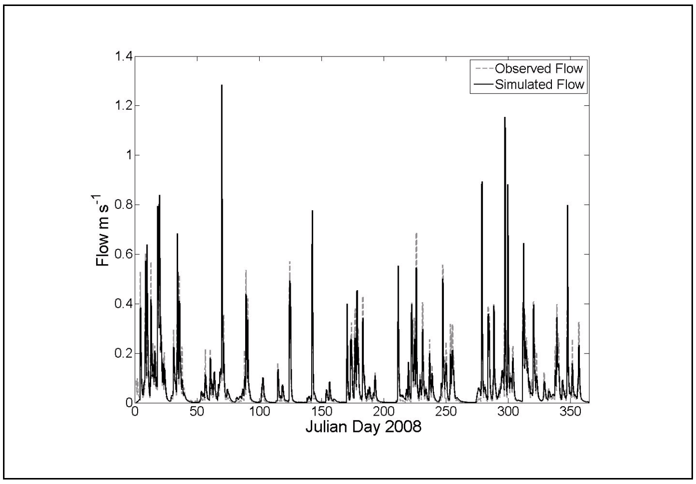

Figure 5.4. Observed and simulated flows for validation year 2008 at hourly intervals.

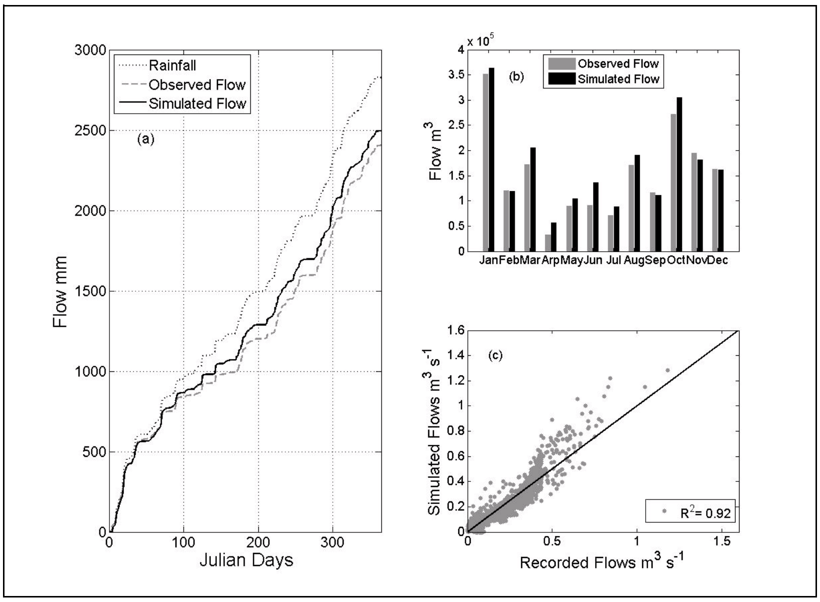

Figure 5.5. (a) Cumulative rainfall, observed flow and simulated flow, (b) monthly observed and simulated flows, and (c) observed and simulated flows, for 2008.

Table 5.2. Observed, calibrated model (2007) and validated model (2008); rainfall, evapotranspiration and stream flow values.

Scenario	Year	Rainfall (mm)	Evapotranspiration (mm)	Streamflow (mm)	Run-off/Rainfall ratio
Observed	2007	2,229	304	1,925	0.75
Calibrated model	2007	2,229	211	2,018	0.82
Observed	2008	2,826	421	2,405	0.85
Validated model	2008	2,826	330	2,496	0.88

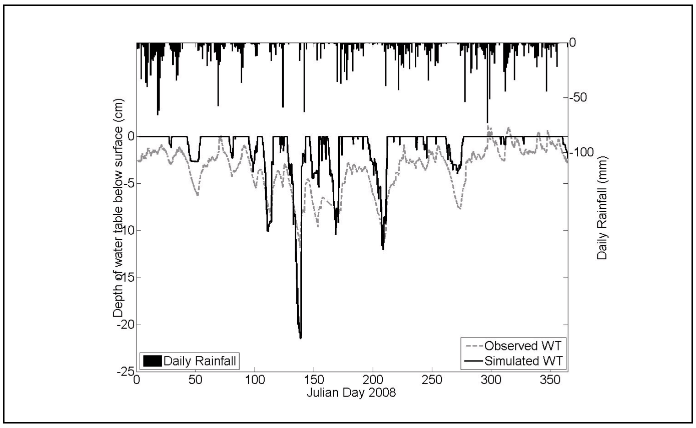

Figure 5.6. Daily rainfall (top) and observed and simulated water table (WT) depth for 2008.

noted that the observed water table is only at one point in the catchment, while the modelled water table level is representative of the total catchment.

Figure 5.7 shows the measured daily stream discharge (m^3/s) and the mean daily concentration of DOC (mg/l) for the years 2007 and 2008. The two clear trends are that the DOC concentration increases in the summer (with increasing temperature) and also increases (but less so) with increasing flow rate. When the DOC increases with flow, it remains elevated for the next few days. Figure 5.8 shows the cumulative stream discharge (mm) and the cumulative DOC export (kg C/ha). The DOC export increases in unison with increasing flow rate. As the DOC export is the product of stream discharge and DOC concentration (normalised to unit area, ha), it is the huge increases in flow rate and not the small increases in DOC concentration that are primarily responsible for the increases in DOC export in Fig. 5.8.

The End of Project Report shows tables of monthly modelled output for 2007 and 2008 at Glencar. The modelled flows are similar to the measured flows. The exported DOC is also similar to the measured DOC. In 2007, the measured DOC export was 0.119 t C/ha by comparison with the modelled values of 0.106 t C/ha. In 2008, the measured DOC export was 0.150 t C/ha and the modelled values were 0.131 t C/ha.

5.3 GEOtop – Munster Blackwater – Three Sub-Catchments

The End of Project Report shows the figures and tables with results of the GEOtop output for stream flow, erosion and loss of SOC for the three Munster Blackwater sub-catchments for 2006. It shows that the model simulates the river flow reasonably well.

5.3.1 GEOtop simulations for land use and climate change

Hypothetical scenarios of land use and climate change in accordance with Tables 5.3 and 5.4 were carried out using GEOtop for the Munster Blackwater Duarrigle catchment. The results, presented in Table 5.5, show that there is an increase in erosion (SSY) and a loss of

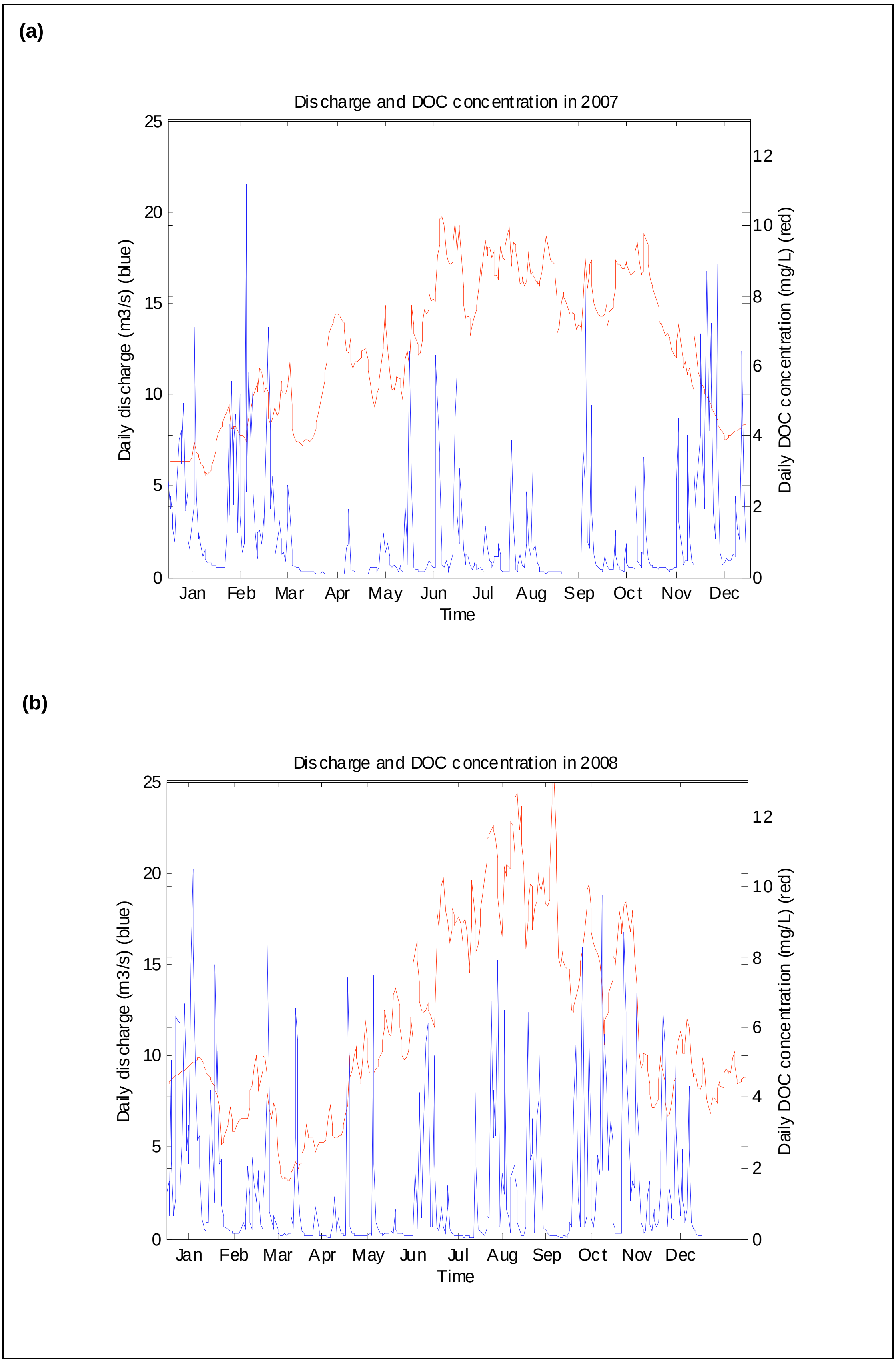

Figure 5.7. For the Glencar peatland, observed daily stream discharge (blue) and daily dissolved organic carbon (DOC) concentration (red) (mg/l) for 2007 and 2008.

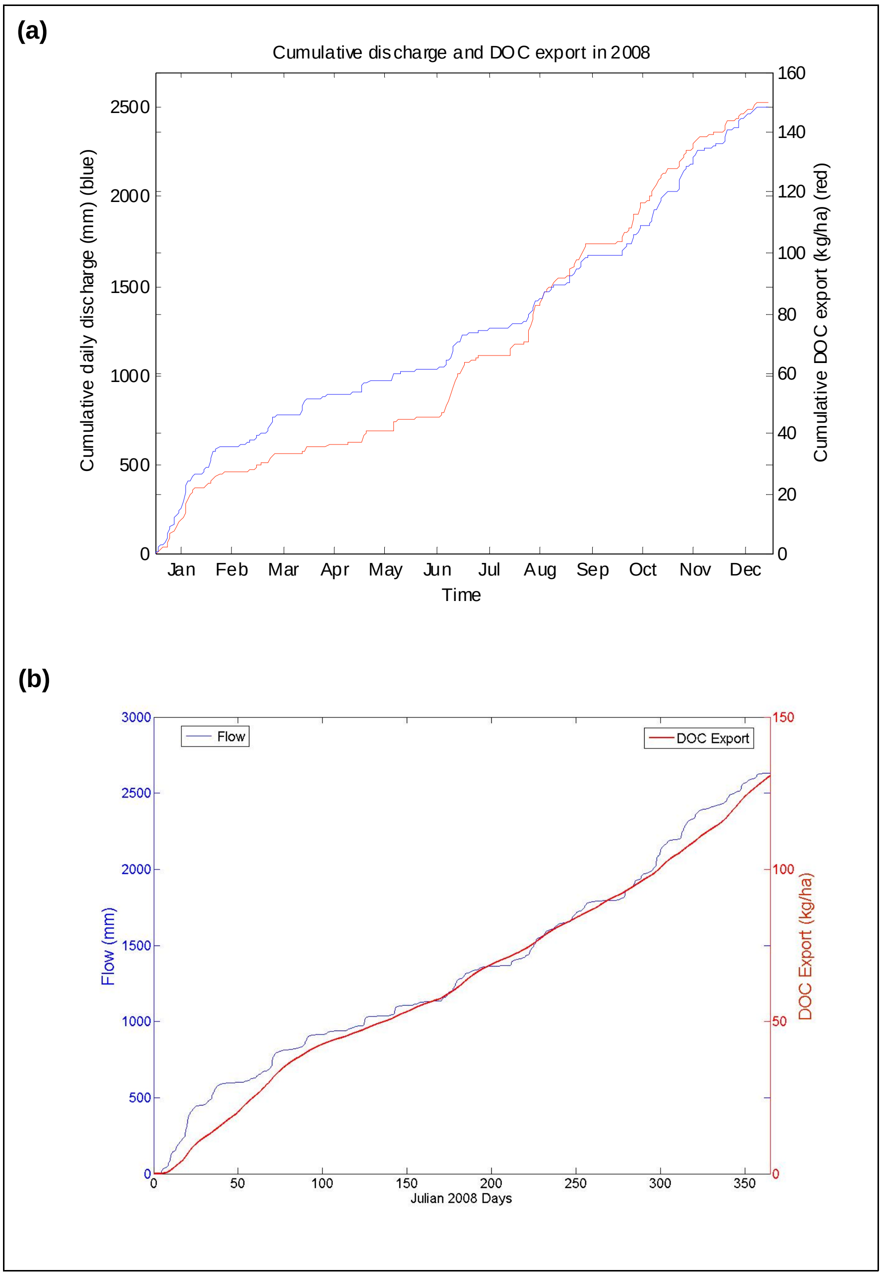

Figure 5.8. For the Glencar peatland (a) observed, and (b) modelled cumulative discharge (mm – blue line) and dissolved organic carbon (DOC) export (kg/ha – red line), for 2008.

Table 5.3. Climate change scenario (2021–2060).

	January–April	May–August	September–December
Rainfall	+15%	–10%	+15%
Temperature	+1.25°C	+1.25°C	+1.25°C

Table 5.4. Land use change (LUC) scenarios.

	LUC-1	LUC-2
All catchments	+10% forestry	+20% forestry

Table 5.5. Duarrigle catchment – land use and climate change effects.

	Non-modified				Land use change + 20% forest				Climate change			
	Rain (mm)	Flow (mm)	Erosion (t/ha)	SOC (t/ha)	Rain (mm)	Flow (mm)	Erosion (t/ha)	SOC (t/ha)	Rain (mm)	Flow (mm)	Erosion (t/ha)	SOC (t/ha)
January	106.17	126.22	0.0116	0.0032	106.17	123.22	0.0116	0.003	106.13	126.21	0.0214	0.0046
February	52.594	54.372	0.0039	0.0030	52.594	52.478	0.0037	0.0029	52.724	54.53	0.0062	0.0035
March	118.25	94.94	0.0204	0.0075	118.25	92.384	0.0301	0.0085	118.6	95.555	0.0159	0.0085
April	54.589	44.655	0.0013	0.0034	54.589	42.135	0.0012	0.0032	54.71	44.539	0.0020	0.0044
May	147.53	102.42	0.0230	0.0111	147.53	99.117	0.0204	0.0103	147.93	102.83	0.0130	0.0092
June	14.072	9.3904	0.0000	0.0006	14.072	8.016	0.0000	0.0005	14.106	9.2752	0.0000	0.0006
July	37.052	12.357	0.0001	0.0009	37.052	10.818	0.0001	0.0007	37.104	12.24	0.0001	0.0008
August	50.106	17.252	0.0002	0.0012	50.106	15.1	0.0001	0.0009	50.1	16.979	0.0001	0.0011
September	213.45	106.03	0.0901	0.0191	213.45	104.59	0.1010	0.0200	213.73	105.57	0.1317	0.0255
October	134.89	128.97	0.0364	0.0142	134.89	126.76	0.0364	0.0141	135.06	127.7	0.0570	0.0187
November	167.24	142.34	0.0575	0.0190	167.24	140.47	0.0576	0.0188	167.54	143.23	0.0869	0.0247
December	204.43	208.69	0.0630	0.0230	204.43	202.26	0.0630	0.0228	205.03	206.22	0.0936	0.0291
SUM	**1,300.3**	**1,047.6**	**0.3079**	**0.1066**	**1,300.3**	**1,017.3**	**0.3256**	**0.1066**	**1,302.3**	**1,044.8**	**0.4293**	**0.1314**

SOC, Soil organic carbon.

SOC. From the baseline situation, the land use change scenario (20% increase in forest) results in a ~10% increase in erosion, while the climate change scenario is an increase of ~50%.

6 GIS Risk Assessment of Threats to Soils

This chapter presents the GIS results of the risk assessment of the threats to soils: *surface sealing*, *erosion*, *loss of organic matter* and *landslides* (Zhang and McGrath, 2004; Zhang et al., 2008, 2011).

6.1 Surface Sealing

The type and areas of surface sealing of Ireland are shown in Table 6.1. Compared with 1990 data, there were significant increases in the discontinuous urban fabric fraction, construction sites, industrial and commercial units, roads, and sport and leisure facilities by 2006. The areas for sea ports and airports remained stable. The value of 50.7 km^2 of continuous urban fabric in 1990 is an overestimate, and may be related to the older techniques of satellite image interpretation. In 2006, the total area of surface sealing in Ireland was 1,500.4 km^2. With the total land area of 71,222.7 km^2, surface sealing accounted for 2.1% of land area in Ireland. The spatial distribution map of surface sealing of Ireland in 2006 is shown in Fig. 6.1.

The spatial distribution maps demonstrate the urban sprawl in Ireland during 1990–2006, which is obvious in the cities. In other smaller urban areas, the urban sprawl feature is also clearly observable. Between 2000 and 2006, the areas of land cover that have been lost to surface sealing are listed in Table 6.2. The area of the change was 206.9 km^2. The main land cover changes were from pasture land and non-irrigated arable land to surface sealing. Based on Table 6.1, the increase of surface sealing from 2000 to 2006 was 198.6 km^2 or 0.278%. The slight difference of 8.3 km^2 could be caused by the change of surface sealing to other land cover types or by inaccuracies during the production of the GIS data.

While surface sealing increased between 1990 and 2006, because of the economic recession it is likely that there has been no additional surface sealing between 2006 and 2014. The value in Table 6.1, of an Irish surface sealing extent of 2.1%, is higher than that estimated by Eaton et al. (2008) and the European Community value of ~1.6%. The latter two projects are based on data up to 2000 and exclude roadways; as noted above, it is estimated that about 0.3% was added between 2000 and 2006. However, if the surface sealing extent in Ireland is compared with Ireland's European neighbours, it is very obvious that their surface sealing problems are much more urgent than those in Ireland. Poorly planned surface sealing leads to urban flood issues.

Table 6.1. Areas of surface sealing of Ireland in 1990, 2000 and 2006 (km^2).

Code	Name	Area_90	Area_00	Area_06	% Area_06
111	Continuous urban fabric	50.7	28.2	28.3	0.0397%
112	Discontinuous urban fabric	711.8	939.7	1,080.1	1.5165%
121	Industrial or commercial units	38.7	79.9	97.4	0.1367%
122	Road and rail networks and associated land	2.6	18.6	42.1	0.0591%
123	Sea ports	10.2	10.4	10.4	0.0146%
124	Airports	21.4	24.1	24.9	0.0349%
133	Construction sites	9.9	27.4	23.4	0.0329%
142	Sport and leisure facilities	93.7	173.5	193.8	0.2721%
	Total	**939.2**	**1,301.8**	**1,500.4**	**2.1066%**

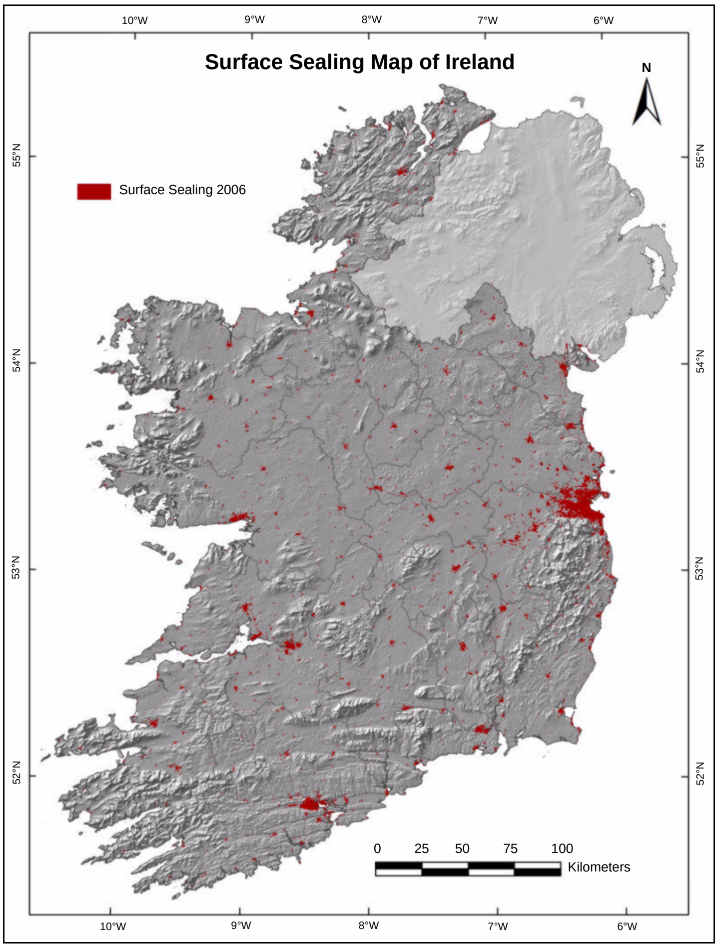

Figure 6.1. Surface sealing map of Ireland, 2006.

Table 6.2. Areas of land cover changed to surface sealing between 2000 and 2006.

CLC code	CLC name	*N* polygons	Area (km^2)
211	Non-irrigated arable land	307	52.2
231	Pastures	966	130.5
242	Complex cultivation patterns	41	4.9
243	Land principally occupied by agriculture with significant areas of natural vegetation	73	10.3
311	Broad-leaved forest	4	0.2
312	Coniferous forest	11	1.5
313	Mixed forest	7	0.8
321	Natural grassland	1	0.1
322	Moors and heathlands	2	0.2
324	Transitional woodland shrub	33	4.5
411	Inland marshes	1	0.1
412	Peat bogs	15	1.7
423	Intertidal flats	1	0.0
Total		**1,462**	**206.9**

CLC, CORINE Land Cover.

6.2 Update of SOC Content Map

A geographically weighted regression (GWR) method (Fotheringham et al., 2002) was used for the spatial modelling and spatial interpolation of SOC in Ireland. A total of 1,310 samples of SOC data were extracted from the NSD (Fay and Zhang, 2007). Environmental factors of rainfall, land cover and soil type were investigated and included as the independent variables to establish the GWR model. The SOC map (Fig. 6.2) showed elevated values in western Ireland where organic soils (or mainly blanket peat) are widespread, as well as the areas with high rainfall. The high values for peat are in the range 40–50% SOC. South-western Ireland and the Wicklow Mountains also exhibit high SOC. These areas are of high elevation and high rainfall, with upland blanket peats. In parts of the midlands of Ireland, there were scattered patches of high SOC areas, which were in line with the distribution of raised peat.

6.3 RUSLE and SEDD Applications in Soil Erosion and Sediment Yield

Soil erosion in Ireland was evaluated using the RUSLE model and sediment delivery using SEDD. To test the data processing method based on literature and the feasibility of using GIS techniques to derive required parameters, the Munster Blackwater catchment to Mallow (with three sub-catchments) was used for modelling with RUSLE and SEDD. Table 6.3 presents the results of some statistical analysis for sediment yield in the different catchments.

Using the default value β = 1.0, the suspended sediment of the individual catchments as estimated by RUSLE and SEDD is generally around or below 1.0 t/ha/year. An exception is the Dripsey catchment, with sediment delivered of 9.1 t/ha/year. Based on Lewis (2003), the measured sediment delivered for 2002 and 2003 on the 15-km^2 Dripsey catchment was ~0.2 t/ha/year and not 9.1 t/ha/year as estimated by RUSLE. However, the use of the default value of 1 for β is not robust, and studies, including Ferro and Porto (2000), used β values in the range 0.02–0.04. If a β value of 0.02 were used instead of the default of 1, then the sediment delivered in the Dripsey 15-km^2 catchment would be 0.18 t/ha/year, which is what Lewis (2003) measured. The watershed-specific parameter β is singularly accountable for the high values in the Dripsey catchment. It needs to be noted

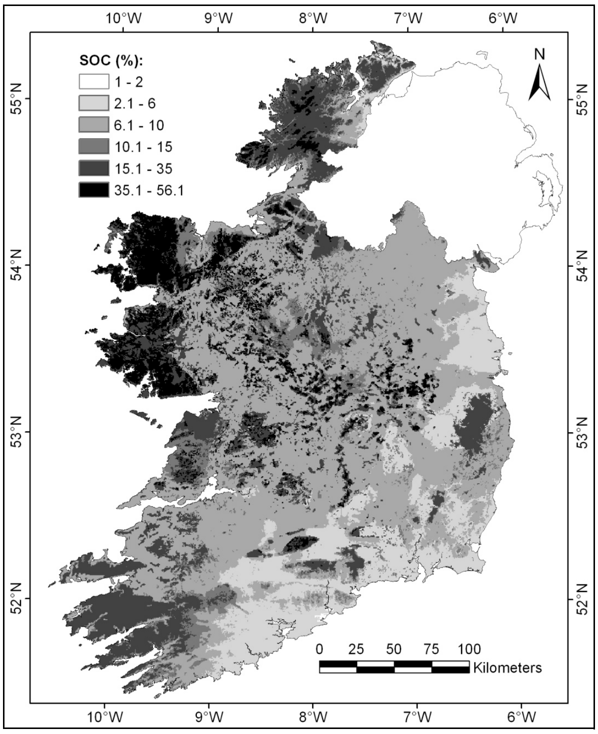

Figure 6.2. Spatial distribution map of soil organic carbon (SOC) in Ireland created using geographically weighted regression.

Table 6.3. Sediment yield statistics for selected catchments (t/ha/year).

Catchment	Area (km²)	Minimum	Median	Maximum	Average
Dromcummer	881	0.0	0.0	984.1	0.15
Duarrigle	245	0.0	0.0	445.9	0.18
Mallow	1186	0.0	0.0	984.1	0.36
Dripsey	15	0.0	0.5	346.0	9.09
Bandon	406	0.0	0.01	642.1	1.29

that due to lack of actual catchment measurement data for the parameters and lack of actual field experiment work in Ireland, the results of soil erosion using RUSLE and SEDD in this study can only be regarded as a first effort.

6.3.1 *National scale*

Using the RUSLE and SEDD models, the final erosion map (Fig. 6.3) for Ireland was produced under the present conditions (of land use and climate).

Tables 6.4 and 6.5 show the statistics for erosion for different land uses. The elevated steep parts of catchments have high erosion values, while flat low-lying areas show no erosion. Results show that the median erosion loss for Ireland is ~0.507 t/ha/year, while for grassland it is 0.454 t/ha/year, for forests it is 0.26 t/ha/year, and for arable land it is 11.36 t/ha/year. According to the soil erosion classification by Zachar (1982), Ireland experiences negligible erosion.

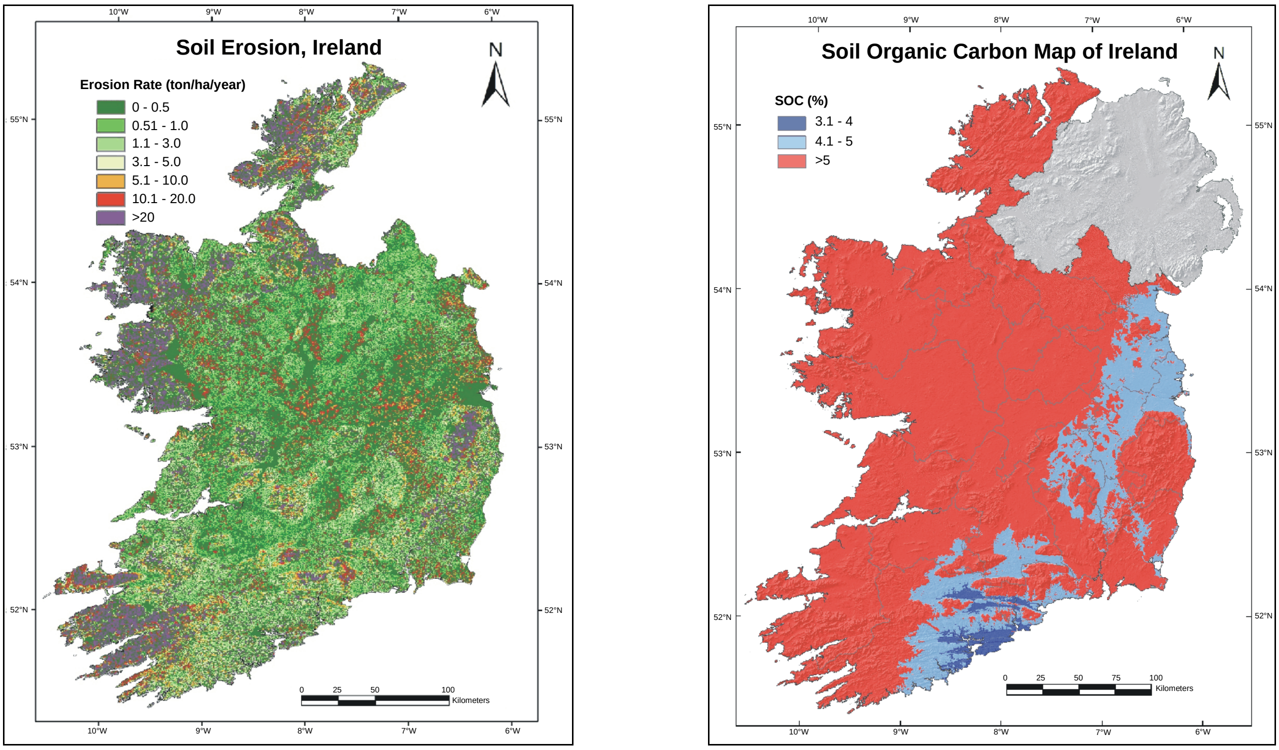

Figure 6.3. (a) Soil erosion risk in Ireland (based on RUSLE model), and (b) spatial distribution map of soil organic carbon (SOC) in Ireland created using geographically weighted regression. The areas of high erosion risk are those in peatlands at elevated locations. Erosion in peatlands is not dissimilar to landslides in peatlands. Unlike Spain, where mineral soil areas with low SOC (<1%) have high erosion risk, Ireland has no known areas with such low SOC values.

Table 6.4. Statistics of erosion for Ireland and its major land cover types.

	%	Minimum (t/ha/year)	Median (t/ha/year)	Maximum (t/ha/year)
Ireland	100.0	0.0	0.5	2,912.6
Pasture	~53.3	0.0	0.5	2,483.1
Forest	~4.2	0.0	0.3	1,957.9
Arable	~7.8	0.0	11.4	316.1

Table 6.5. Erosion distribution for Ireland and its major land cover types.

(t/ha/year)	Ireland (%)	Pasture (%)	Forest (%)	Arable (%)
0–0.75	55.3	59.5	35.6	44.0
0.75–7.5	22.5	31.4	10.7	8.4
7.5–22.5	6.3	4.2	50.0	19.9
22.5–75	5.7	2.8	0.7	20.8
75–300	5.2	1.5	1.6	6.9
>300	5.1	0.6	1.4	0.01

With SEDD, the national mean sediment yield across Ireland for pasture was 0.068 t/ha/year, for forest it was 0.098 t/ha/year, and for arable land it was 0.22 t/ha/year. It is interesting to note that practically 100% of SSY distribution fell into the 0–0.75 t/ha/year band, with very few pixels outside this range. The results show that the final sediment yield in Ireland is at a low level and that arable lands suffer more erosion than forests and pasture.

Table 6.6 suggests different SDRs for different land uses: 0.15 for grassland, 0.37 for forestry and 0.02 for arable land. An earlier review of the literature suggested SDR values in the range 0.1 to 0.8. In the context of erosion, sediment yield and loss of SOC, it is important to distinguish between the soil types and between the different land covers. Mineral soils respond differently to peat soils. Peat soils cover approximately 18% of the Irish landscape. Pristine peat areas have little erosion, except on very upland steep areas. Pristine peat loses very little soil, and its carbon in fluvial loss is primarily lost as DOC of the order of 0.1 t/ha/year. However, in non-pristine peat areas where grazing or harvesting has occurred, significant erosion, which can mobilise particulate organic matter, can occur and losses of particulate

Table 6.6. Summary of RUSLE and SEDD values for Ireland.

	%	Erosion median (t/ha/year)	SSY median (t/ha/year)
Ireland	100.0	0.5	
Pasture	~53.3	0.5	0.07
Forest	~4.2	0.3	0.10
Arable	~7.8	11.4	0.22

RUSLE, Revised Universal Soil Loss Equation model; SEDD, Sediment Delivery model; SSY, suspended solids yield.

matter may far exceed the losses of DOC. In the UK work on degraded upland blanket peatlands, POC losses are of the order of 0.5 to 1 t/ha/year.

6.3.2 Climate and land use change scenarios

Risk assessment was performed based on different soil erosion risk scenarios concerning the changes of climate and land use. The predicted climate change data were obtained from the C4i project. The statistical results of soil erosion distribution under different scenarios are displayed in the End of Project Report. The soil loss distribution frequencies were counted based on six groups: 0–0.75, 0.75–7.5, 7.5–22.5, 22.5–75, 75–300 and >300 (t/ha/year). It showed a dramatic change in arable scenarios when forests and pastures are converted to arable lands during the model simulation. The climate change scenarios resulted in less change than the land use change scenarios. The results for the different scenarios indicated that land use change from grass and forests to arable lands has the most significant impact on soil loss.

6.4 Landslides

Ireland is a comparatively benign environment as far as landslides are concerned compared with elsewhere in the EU (e.g. Italy and France), with 136 recorded by the GSI for Ireland. However, events in recent years have indicated that damage can be caused by landslides. It is therefore important to better understand and map these hazards. This study investigated the relationship between landslides and elevation (Fig. 6.4). It was found that many landslides were in areas with high elevations, especially in the eastern (Dublin–Wicklow Mountains), south-western (Kerry Mountains) and north-western parts of Ireland.

The frequencies of landslides and their associated soils are summarised in Fig. 6.5. The results show almost half of the landslide events (63) had peat as the main soil, while some landslides were composed of coarse debris. There were 36 events with unspecified materials.

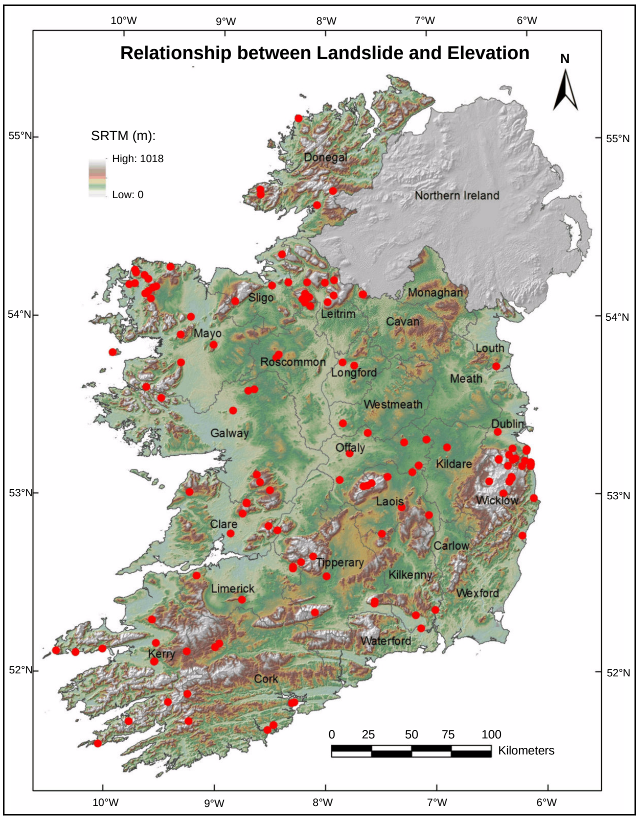

Figure 6.4. Relationship between landslides and elevation. Known landslides shown as red dots. SRTM, Shuttle Radar Topography Mission.

Landslides involving peat, in both raised and blanket bogs, make up the largest number of events in the Irish Landslides Database. The spatial relationship between landslides and peat is shown in Fig. 6.6a. The close relationship between landslides and peat is clearly shown in western and south-western Ireland, as well as in the Wicklow Mountains. A landslide hazard map was produced using the kernel density method (Fig. 6.6b). For this method, a smoothly curved surface is fitted over each point. The surface value is highest at the location of the point and diminishes with increasing distance from the point. Density values are added for each point. Areas featuring high kernel densities of landslides were in County Dublin and County Wicklow, north County Mayo and County Leitrim, especially in the mountain areas of these counties. There was also a good relationship between the high-density landslide areas and high elevations.

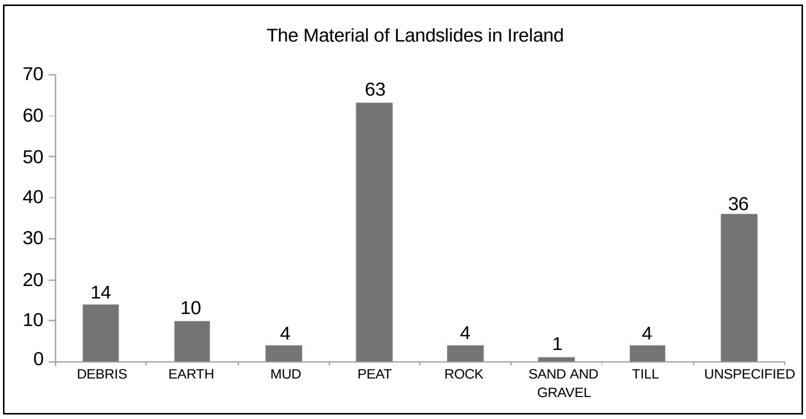

Figure 6.5. Frequencies of landslide materials in Ireland.

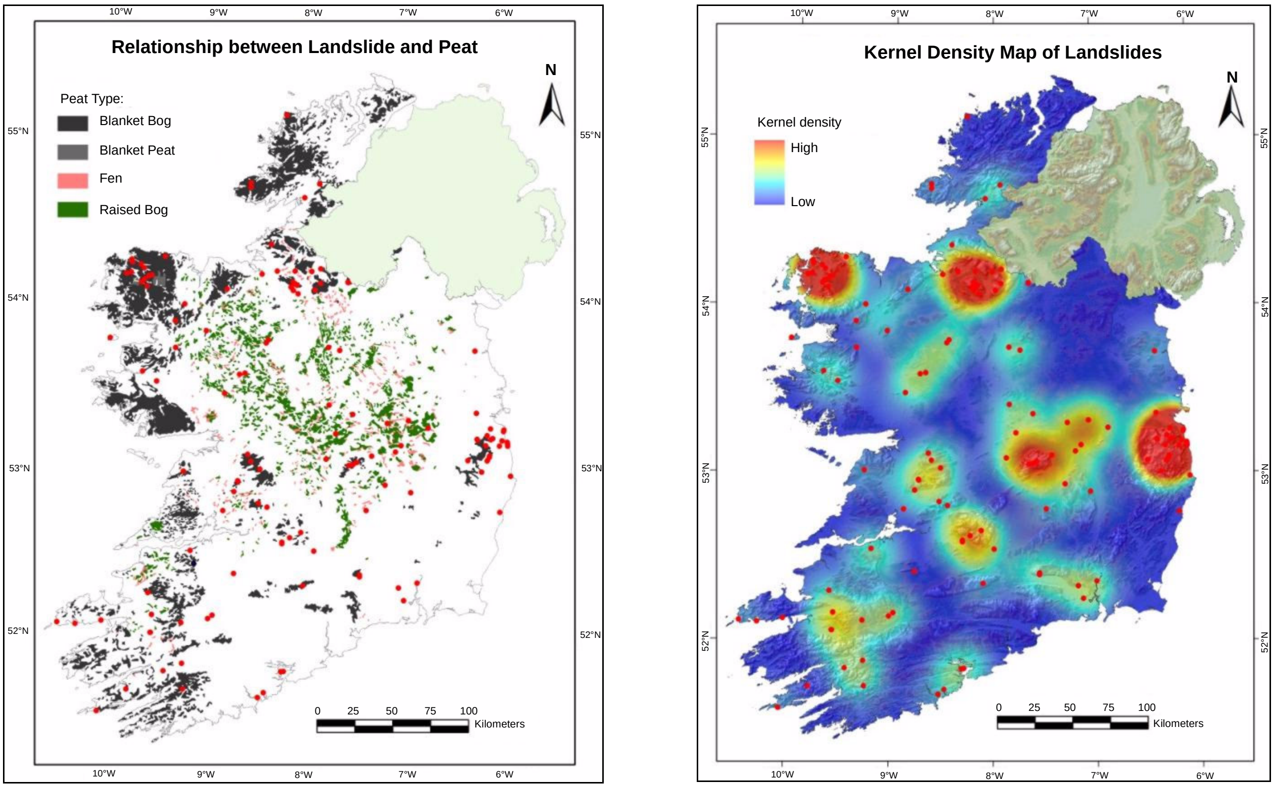

Figure 6.6. (a) Relationship between landslides and peat (known landslides shown as red dots), and (b) estimated kernel density map of landslides in Ireland.

7 Discussion and Conclusions

The project's tasks can be abbreviated as follows:

1. Determine the SHPs of a range of Irish soils under different land uses;
2. Identify a hydrological classification of Irish soils; and
3. Examine the threats to Irish soils from erosion, loss of OM, compaction, surface sealing (urbanisation) and landslides.

A brief discussion on the results and their meaning (under the above three headings) is presented here and this is followed with a section on conclusions.

7.1 Discussion

7.1.1 SHPs

Knowledge and understanding of SHPs are essential for studies to examine the behaviour and response of soils and catchments to rainfall events, land use and land use change and climate change. This understanding can then be used in simulation studies – such as rainfall/run-off modelling – to examine the threats to soils such as erosion, loss of OM, compaction, surface sealing (urbanisation) and landslides.

The SHPs of interest are hydraulic conductivity and the water retention characteristics. Prior to quantifying the SHPs (at different depths), some key physical, moisture and chemical properties of soils were first determined, including:

- Bulk density;
- Porosity; texture (% SSC);
- Saturation moisture content;
- Infiltration characteristics (e.g. rate of infiltration at saturation); and
- % SOC.

Thirty-one mineral soil sites throughout Ireland (three depths: 0, 15 and 30 cm; and three replicates) were sampled for all of the above soil properties. One pristine blanket peatland was also sampled for a 200-m transect (14 locations and depths up to 5 m).

The authors found that most of the mineral soils sampled were loams from the medium-loam classification of the USDA soil textural triangle. The % SOC for the mineral sites ranged from lows of ~2% to highs of <10% and that the bulk densities ranged from ~0.9 to 1.4 g/cm^3 but were lower than what was expected from their textural classification. This was due to a number of factors, including high % SOC and frequent soil wetting, which enables macroporosity and good soil structure to prevail. It was found that the porosity was higher than expected from textural classification. The high porosity is considered to be due to the presence of macropores facilitated by the perennial low-intensity rainfall characteristic of the Irish climate.

For the pristine blanket peatland, it was found that the bulk density at the edges of the peatland boundary (e.g. near the stream) was 0.11 g/cm^3 or twice that at the bog centre. No increase of bulk density with depth was found, even as deep as 5 m. Conversely, the horizontal saturated hydraulic conductivity was two to three orders of magnitude less conductive at the edges than it was at the bog centre. In general, the horizontal hydraulic conductivity was about twice the vertical hydraulic conductivity.

7.1.2 Hydrological classification of Irish soils

Because of the continuous wetness of many of the sites during the sampling period (summer 2008 and summer 2009), it was not possible to use the BEST method of analysis of the infiltration tests and the authors had to rely on a variant of it. However, they were able to determine the key hydrological properties of the mineral sites sampled, although it was not possible to produce a hydraulic classification of Irish soils in accordance with the more widespread classifications of Schaap and Leij (2000) or Clapp and Hornberger (1978), using simple textural divisions and PTFs composed of soil properties such as % SSC and

% SOC. The aim was to identify a reliable classification that would maximise the difference in hydraulic properties among different textural classes but minimise the difference within each class. The data did not show significant difference between the conventional textural classifications. The IFS classification (deep, well-drained mineral, shallow, well-drained mineral, etc.) is a suitable hydraulic classification for Irish soils. Irish soils are somewhat different to soils in other climates, due to the high SOC content, the perennial wet climate and the widespread grassland cover. Therefore, a quantifiable hydraulic classification similar to that of the IFS was produced. The existing IFS classification is qualitative and so cannot be used for hydrological modelling. However, the quantification of the IFS classification enables it to be used for modelling purposes. This classification is:

- Deep, well-drained mineral soils; $K_S \approx 166 \pm 534$ cm/day;
- Shallow, well-drained mineral soils; $K_S \approx 22$ cm/day;
- Deep, poorly drained mineral; $K_S \approx 7.8 \pm 6.8$ cm/day;
- Poorly drained mineral with peaty topsoil; $K_S \approx 3.1$ cm/day;
- Alluvia; $K_S \approx 14.2$ cm/day; and
- Peats; $K_S \approx 1{,}030$ cm/day at bog centre and 1.03 cm/day at bog edge.

7.1.3 Threats to Irish soils

Using a combination of the above results (of soil physical, chemical and hydrological properties) and a process-based distributed rainfall/run-off model (GEOtop), the study examined the three threats to Irish soils of erosion, loss of OM (or SOC) and compaction. While there are very few data from field experiments within Ireland for erosion, loss of SOC and compaction, the simulations provide insight to these three threats to Irish soils. It was found that erosion in Ireland is likely to be at the lower end of the international scale at levels <1 t/ha/year and associated SSY to rivers of the order of ~0.2 t/ha/year. Erosion-produced SOC, which ends up in suspended sediment in streams, is of the order of 10 kg/ha/year. The SOC loss is in the range 2.5–4.5% of the in-stream sediment.

From the study's field experiments of compaction and the lower than expected bulk densities (from textural analysis), it is estimated that there is little compaction in the mineral soils sampled. The simulations of compaction using GEOtop (allowing bulk density to increase with associated decrease in hydraulic conductivity) show very clearly that compaction results in higher instantaneous flood peaks, higher erosion and greater loss of SOC than for uncompacted soils. The changed partitioning of precipitation (infiltration vs surface run-off) after compaction causes decreases in infiltration and increases in surface run-off, resulting in greater flood peaks, more erosion and greater SOC loss.

The simulations of land use change in the Glencar peatland (increased forestry percentage of catchments) and climate change (more rainfall in winter and less in summer) show that land use change has a more negative impact. This was demonstrated by significant increases in evapotranspiration resulting in less stream run-off. The peatland measurements and modelling show that carbon lost as DOC in stream flow ranges from ~10 kg/ha/year to ~150 kg/ha/year. Low DOC export levels are associated with catchments dominated by mineral soils, while the highest values are associated with streams running through peatland.

The threats to soil quality from surface sealing (urbanisation) and landslides were examined using GIS techniques. It was found that Ireland has undergone rapid surface sealing in recent decades. Up to 2000, it was estimated that urban areas covered ~0.4% of the Irish land area, while urban plus suburban and road infrastructure covered close to 1.6%. However, using data up to 2006, the updated estimate of total surface sealing is ~2.1%. This compares with an EU range of 0.15% (Iceland) to 13.3% (Malta). By comparison, the values for the UK are 3.3% and Germany 5.1%. It is important to reflect in spatial planning strategies that the loss of agricultural soil to surface sealing is irreversible, and likely to have long-term effects on agriculture, forestry, ecology and soil functions (e.g. loss of carbon sinks). Furthermore, whatever form it takes, urban growth leads to reduced groundwater availability and urban planners should consider no growth or reduced growth scenarios in areas dependent on groundwater. The recent urbanisation is likely to have led to increased frequency of urban flooding.

With regard to landslides, the GSI recorded a total of 117 landslides up to 2006 and 136 by 2009. This compares with ~500,000 in Italy. Nearly half of the landslides in Ireland are in peatlands (63 of the 136), and are partly the result of rainfall patterns of wet periods following dry periods and partly due to the influence of peat harvesting and construction activities. Although landslides can occur at any elevation, the authors found the factors most influencing landslides to be mountainous areas, a land cover of peat, and sloping land. Landslides tended to occur in clusters, in locations where the influencing factors were present. Landslides of mineral soils at cliffs and coastal areas due to coastal erosion are likely to become more significant in the future due to climate change, sea level rise and increasing intensity of storms and sea surges.

7.1.4 Relevance to policy

This report finds that the threats (erosion, loss of OM, compaction, surface sealing and landslides) to Irish soils under current land use, management and climate conditions are low by international comparisons. This suggests that Irish soil quality is likely to be sustainable as currently managed. However, there are potential risks to continued sustainability of soil quality associated with intensification of food production in Ireland. In this context, there is an immediate need for comprehensive research to address the possible impact on soil quality of the implementation of *Food Harvest 2020*. There is also an urgent need to address the potential impact of wind farm infrastructure on peatlands, and in particular on the structural integrity of peatlands.

7.2 Conclusions

The study found no evidence of widespread soil degradation across the Irish sites that were examined in this project. This is in contrast to our EU neighbours, who suffer widely from the threats examined in this project. There is little evidence of widespread erosion or loss of SOC, and that which does occur is at a low rate by international comparison. Similarly, there is little evidence of widespread compaction of the Irish soils examined, and the naturally occurring perennial low-intensity rainfall and high levels of SOC, combined with the widespread land cover of grassland, seem to insulate Irish soils from compaction. Surface sealing (or urbanisation) has increased significantly, particularly since 1990, with urbanisation (plus suburbanisation and road infrastructure) now at ~ 2.1% of the total land area. This increase has brought problems of inadequate services (e.g. water, wastewater and solid waste treatment) and potential for increased urban and more frequent road infrastructure flooding. However, the 2.1% is low on the international scale. Most EU countries are at levels twice this or more. Of the 136 landslides documented by the GSI, almost half are in peatlands and most are recent, and are attributed to climate effects, road construction and other infrastructural development. However, on the international scale Ireland has few landslides.

While rainfall extremes and flooding were not in the brief of this project, it is very clear to the authors that these extremes may be the cause of much greater threats to soils (and to the economy and safety of life) than the threats that were examined in this report. The authors recommend that the EPA addresses rainfall extremes with consequent threats of flooding as a potential threat to soils. Since there is very little field experimental research in Ireland on erosion, loss of SOC and compaction, it is recommended that the EPA addresses field experimental research at the catchment scale. This will also enable more robust modelling efforts using RUSLE, SEDD or process-based rainfall/run-off models (e.g. GEOtop).

References

Assouline, S., 2006a. Modeling the relationship between soil bulk density and the water retention curve. *Vadose Zone Journal* **5:** 554–563.

Assouline, S., 2006b. Modeling the relationship between soil bulk density and the hydraulic conductivity function. *Vadose Zone Journal* **5:** 697–705.

Beckwith, C.W., Baird, A.J. and Heathwaite, A.L., 2003. Anisotropy and depth-related heterogeneity of hydraulic conductivity in a bog peat. I: Laboratory measurements. *Hydrological Processes* **17(1):** 89–101.

Bertoldi, G., Rigon, R. and Over, T.M., 2006. Impact of watershed geomorphic characteristics on the energy and water budgets. *Journal of Hydrometeorology* **7(3):** 389–403.

Beven, K.J., 2001. *Rainfall-Runoff Modelling – The Primer*. Wiley, Chichester, UK.

Boardman, J. and Poesen, J., 2006. *Soil Erosion in Europe: Major Processes, Causes and Consequences*. Wiley, Chichester, UK.

CEC (Commission of the European Communities), 2006. *Thematic Strategy for Soil Protection*, COM(2006)231 final. CEC, Brussels, Belgium.

Cerdan, O., Poesen, J., Govers, G., Saby, N., Le Bissonnais, Y., Gobin, A., et al., 2006. Sheet and rill erosion. *In:* Boardman, J. and Poesen, J. (Eds), *Soil Erosion in Europe: Major Processes, Causes and Consequences*. Wiley, Chichester, UK. pp. 501–513.

Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., et al., 2010. Rates and spatial variation of soil erosion in Europe: A study based on erosion plot data. *Geomorphology* **122:** 167–177.

Clapp, R.B. and Hornberger, G.M., 1978. Empirical equations for some soil hydraulic properties. *Water Resources Research* **14(4):** 601–604.

Cogle, A., Rao, K., Yule, D., Smith, G.D., George, P.J., Srinivasen, S.T. and Jangaard, L., 2002. Soil management for alfisols in the semi-arid tropics: Erosion, enrichment ratios and runoff. *Soil Use Management* **18:** 10–17.

Creighton, R., 2006. *Landslides in Ireland*. Irish Landslides Working Group, Geological Survey of Ireland, Dublin, Ireland.

DAFM (Department of Agriculture, Food and the Marine), 2010. *Food Harvest 2020.* Available at http://www.agriculture.gov.ie/agri-foodindustry/foodharvest2020 [accessed 18 August 2013].

DeRoo, A.P.J., Wesseling, C.G. and Ritsema, C.J., 1996. LISEM: A single-event physically based hydrological and soil erosion model for drainage basins. 1. Theory, input and output. *Hydrological Processes* **10(8):** 1107–1117.

Dykes, A. P. and Warburton, J., 2007. Mass movements in peat: A formal classification scheme. *Geomorphology* **86:** 73–93.

Dykes, A.P. and Warburton, J., 2008. Failure of peat-covered hillslopes at Dooncarton mountain, Co. Mayo, Ireland: Analysis of topographic and geotechnical factors. *Catena* **72(1):** 129–145.

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P. and Kiely, G., 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. *Climatic Change* **91:** 317–334.

EEA (European Environment Agency), 2012. *Urban Adaptation to Climate Change in Europe: Challenges and Opportunities for Cities together with Supportive National and European Policies*. EEA Report 2/2012, Copenhagen, Denmark.

Endrizzi, S., Dall'Amico, M., Gruber, S. and Rigon, R., 2011. *GEOtop Users Manual*. Civil and Environmental Engineering Department, University of Trento, Italy.

EPA (Environmental Protection Agency), 2009. *CORINE Land Cover – Ireland. Land Cover Update for 2006 – Final Report*. EPA, Johnstown Castle Estate, Wexford, Ireland.

Evans, D.J., Gibson, C.E. and Rossell, R.S., 2006. Sediment loads and sources in heavily modified Irish catchments: A move towards informed management strategies. *Geomorphology* **79:** 93–113.

Evans, R., 1996. *Soil Erosion and Its Impacts in England and Wales*, Friends of the Earth Trust, London, UK.

Fay, D. and Zhang, C., 2007. *Towards a National Soil Database*. Datasets and digital information objects connected to this resource are available at: Secure Archive for Environmental Research Data (SAFER), managed by EPA. Available at: http://erc.epa.ie/safer/iso19115/displayISO19115.jsp?isoID=105#files

Fay, D., McGrath, D., Zhang, C., Carrigg, C., O'Flaherty, V., Carton, O.T. and Grennan, E., 2007. *Towards a National Soil Database*. Report (2001-CD/S2-M2) to Environmental Protection Agency. EPA, Johnstown Castle Estate, Wexford, Ireland.

Ferro, V. and Porto, P., 2000. Sediment delivery distributed model (SEDD). *Journal of Hydrologic Engineering* **5(4):** 411–422.

Fotheringham, A.S., Brunsdon, C. and Charlton, M.E., 2002. *Geographically Weighted Regression: The*

Analysis of Spatially Varying Relationships. Wiley, Chichester, UK.

Gardiner, M.J. and Radford, T., 1980. *Soil Associations of Ireland and Their Landuse Potential – Explanatory Bulletin to Soil Map of Ireland 1980*. The Agricultural Institute, Dublin, Ireland.

Hamza, M.A. and Anderson, W.K., 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research* **82:** 121–145.

Harrington, S.T and Harrington, J.R., 2011. The influence of storm based events on the suspended sediment flux in a small scale river catchment in Ireland, *6th International Conference on River Basin Management*, May, Riverside, CA, USA.

He, Y., 2010. *Estimating soil erosion and sediment yield with GIS, RUSLE and SEDD: A case study in Ireland*. MA thesis, National University of Ireland, Galway, Galway, Ireland.

Horton, R., Ankeny, M.D. and Allmaras, R.R., 1994. Effects of compaction on soil hydraulic properties. *In:* Soane, B.D. and van Ouwerkerk, C. (Eds) *Soil Compaction in Crop Production*. Elsevier Science B.V., Amsterdam, Netherlands. pp. 479–500.

IPCC (Intergovernmental Panel on Climate Change), 2001. *Climate Change 2001: Synthesis Report: Contribution of Working Groups I, II and III to the Third Assessment Report*. Cambridge University Press, Cambridge, UK.

Jones, A., Montanarella, L. and Jones, R., 2005. *Soils Atlas of Europe*. EC/JRC/EU Soil Bureau Network, Ispra, Italy.

Jones, R.J.A., Hiederer, R., Rusco, E., Loveland, P.J. and Montanarrela, L., 2005. Estimating carbon in the soils of Europe for policy support. *European Journal of Soil Science* **56:** 655–671.

Jordan, P., Menary, W., Daly, K., Kiely, G., Morgan, G., Byrne, P. and Moles, R., 2005. Patterns and processes of phosphorus transfer from Irish grassland soils to rivers – Integration of laboratory and catchment studies. *Journal of Hydrology* **304(1):** 20–34.

Kiely G., 1999. Climate change in Ireland from precipitation and streamflow observations. *Advances in Water Resources* **23(2):** 141–151.

Kiely, G., McGoff, N., Eaton, J., Leahy, P., Xu, X. and Carton, O., 2010. *SoilC – Measuring and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils*. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland. ISBN: 978-1-84995-320-6.

Koehler, A.K., Murphy, K., Kiely, G. and Sottocornola, M., 2008. Seasonal variation of DOC concentration and annual loss of DOC from an Atlantic blanket bog in South-western Ireland. *Biogeochemistry* **95(2–3):** 231–242.

Kutilek, M. and Nielsen, D., 1994. *Soil Hydrology*, Catena Verlag, Reiskirchen, Germany.

Lassabatere, L., Angulo-Jaramillo, R., Soria Ugalde, J.M., Cuenca, R., Braud, I. and Haverkamp, R., 2006. Beerkan estimation of soil transfer parameters through infiltration experiments – BEST. *Soil Science Society America of Journal* **70:** 521–532.

Leahy, P. and Kiely, G., 2011. Short duration rainfall extremes in Ireland: Influence of climatic variability. *Water Resources Management*: **25(3):** 987–1003.

Lewis, C., 2003. *Phosphorus, Nitrogen and Suspended Sediment loss from Soil to Water from Agricultural Grassland*. MEngSc thesis, University College Cork, Cork, Ireland.

Lewis, C., 2011. *Measurement and Modelling of Soil Hydrological Properties for Use in the Distributed Rainfall Runoff Model – GEOtop*. PhD thesis, University College Cork, Cork, Ireland.

McGrath, R., Nishimura, E., Nolan P., Semmler, T., Sweeney, C. and Wang, S., 2005. *Climate Change: Regional Climate Model Predictions for Ireland* (2001-CD-C4-M2). Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland.

McGrath, R. and Lynch, P., 2008. *Ireland in a Warmer World*. Community Climate Change Consortium for Ireland (C4I), Dublin, Ireland.

Minasny, B. and McBratney, A.B., 2007. Estimating the water retention shape parameter from sand and clay content. *Soil Science Society of America Journal* **71:** 1105–1110.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., et al., 2000. *IPCC Special Report on Emissions Scenarios*. Cambridge University Press, Cambridge, UK.

Owens, P.N., Batalia, R.J., Collins, A.J., Gomez, B., Hicks, D.M., Horowitz, A.J., et al., 2005. Fine-grained sediment in river systems: environmental significance and management issues. *River Research and Applications* **21:** 693–717.

Pachepsky, Y. and Rawls, W.J., 2004. *Development of Pedotransfer Functions in Soil Hydrology*. Elsevier, Amsterdam, The Netherlands.

Quinton, J.N., Catt, J.A., Wood, G.A. and Steer, J., 2005. Soil carbon losses by water erosion: Experimentation and modeling at field and national scales in the UK, *Agriculture, Ecosystems and Environment* **112:** 87–102.

Quinton, J.N., Catt, J.A., Wood, G.A., and Steer, J., 2006. Soil carbon losses by water erosion: Experimentation and modeling at field and national scales in the UK. *Agriculture, Ecosystems & Environment* **112(1):** 87–102.

Reeve, A.S., Siegel, D.I. and Glaser, P.H., 2000. Simulating vertical flow in large peatlands. *Journal of Hydrology* **227(1–4):** 207–217.

Rigon, R., Bertoldi, G. and Over, T.M., 2006. GEOtop: A distributed hydrological model with coupled water and energy budgets. *Journal of Hydrometeorology* **7(3):** 371–388.

Saxton, K.E., Rawls, W.J., Romberger, J.S. and Papendick, R.I., 1986. Estimating generalised soil water characteristics from texture. *Soil Science Society of America Journal* **50:** 1031–1036.

Scanlon, T., Kiely, G. and Amboldi, R., 2005. Model determination of non-point source phosphorus transport pathways in a fertilised grassland. *Hydrological Processes* **19:** 2801–2814.

Schaap, M.G. and Leij, F.J., 2000. Improved prediction of unsaturated hydraulic conductivity with the Mualem–van Genuchten model. *Soil Science Society of America Journal* **64(3):** 843–851.

Schaap, M.G., Leij, F.J. and van Genuchten, M.T., 2001. ROSETTA: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology* **251(3–4):** 163–176.

Sherman, L.K., 1932. Streamflow from rainfall by the unit-graph method. *Engineering News Record* **108:** 501–505.

Simoni, S., Zanotti, F., Bertoldi, G. and Rigon, R., 2008. Modelling the probability of occurrence of shallow landslides and channelized debris flows using GEOtop-FS. *Hydrological Processes* **22(4):** 532–545.

Sottocornola, M., Laine, A., Kiely, G., Byrne, K.A. and Tuittila, E.S., 2009. Vegetation and environmental variation in an Atlantic blanket bog in South-western Ireland. *Plant Ecology* **203(1):** 69–81.

Tomlinson, R.W. and Davidson, L., 2000. Estimates of carbon stores in four northern Irish lowland raised bogs. *SUO* **15(3):** 169–179.

Tunney, H., Kurtz, I., Daly, K., Morgan, G., Kiely, G. and Mills, P., 1997. *Quantification of P Loss to Water Due to Soil P Desorption*. EPA First Annual Report January 1997. Environmental Protection Agency, Johnstown Castle Estate, Wexford, Ireland. 26 pp.

Van Beek, C. and Toth, G., 2012. *Risk Assessment Methodologies of Soil Threats in Europe: Status and Options for Harmonisation for Risks by Erosion, Compaction, Salinization, Organic Matter Decline and Landslides.* JRC Scientific and Policy Reports 55496, Ispra, Italy.

Van-Camp, L., Bujarrabal, B., Gentile, A.R., Jones, R.J.A., Montanarella, L., Olazabal, C. and Selvaradjou, S.K. (Eds), 2004. *Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection, Volume II: Erosion*, EUR 21319 EN/2. Office for Official Publications of the European Communities, Luxembourg.

van Genuchten, M.Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Science Society of America Journal* **44:** 892–898.

Van Oost, K. and Govers, G., 2006. Tillage erosion. *In:* Boardan, J. and Poesen, J. (Eds), *Erosion in Europe*. Wiley, Chichester, UK, pp. 599–608.

Verstraeten, G., and Poesen J., 2001. Modelling the long-term sediment trap efficiency of small ponds. *Hydrological Processes* **15(4):** 2797–2819.

Warburton, J., Holden, J. and Mills, A.J., 2004. Hydrological controls of surficial mass movements in peat. *Earth-Science Reviews* **67(1–2):** 139–156.

Wellock, M., LaPerle, C. and Kiely, G., 2011a. What is the effect of afforestation on the carbon stock of Irish mineral soils? *Forest Ecology and Management* **262:** 1589–1596.

Wellock, M.L., Reidy, B., LaPerle, C.M., Bolger, T. and Kiely, G., 2011b. Soil organic carbon stocks of afforested peatlands in Ireland. *Forestry* **84(4):** 441–451.

Wu, L., Pan, L., Mitchell, J., and Sanden, B., 1999. Measuring saturated hydraulic conductivity using a generalized solution for single-ring infiltrometers. *Soil Science Society of America Journal* **63:** 788–792.

Zachar, D., 1982. Soil erosion. *Developments in Soil Sciences,* Vol. 10. Elsevier, Amsterdam.

Zhang, C. and McGrath, D., 2004. Geostatistical and GIS analyses on soil organic carbon concentrations in grassland of southeastern Ireland from two different periods. *Geoderma* **119:** 261–275.

Zhang, C.S., Fay, D., McGrath, D., Grennan, E. and Carton, O.T., 2008. Use of trans-Gaussian kriging for national soil geochemical mapping in Ireland. *Geochemistry: Exploration, Environment, Analysis* **8:** 255–265.

Zhang, C., Tang, T., Xu, X. and Kiely, G., 2011. Towards spatial geochemical modeling: Use of geographical weighted regression for mapping soil organic carbon contents in Ireland. *Applied Geochemistry* **26(7):** 397–441.

Zi, T., 2014. *Reduction of Uncertainties of Physically Based Distributed Soil Water Erosion Model*. Civil and Environmental Engineering Department, Duke University, Durham, NC, USA.

Scientific Contribution of this Project

Theses

He, Y., 2010. *Estimating soil erosion and sediment yield with GIS, RUSLE and SEDD: A case study in Ireland*. MA thesis, National University of Ireland, Galway, Galway, Ireland.

Lewis, C., 2011. *Measurement and Modelling of Soil Hydrological Properties for Use in the Distributed Rainfall Runoff Model – GEOtop*. PhD thesis, University College Cork, Cork, Ireland.

Zi, T., 2014. *Reduction of Uncertainties of Physically Based Distributed Soil Water Erosion Model*. Civil and Environmental Engineering Department, Duke University, Durham, NC, USA.

Peer-Reviewed Papers Published

Dao, L.G., Morrison, L., Kiely, G. and Zhang. C.S., 2012. Spatial distribution of potentially bioavailable metals in surface soils of a contaminated sports ground in Galway, Ireland. *Environmental Geochemistry and Health* **35(2):** 227–238.

Khalil, I., Kiely, G., O'Brien, P. and Müller, C., 2012. Organic carbon stocks in agricultural soils in Ireland using combined empirical and GIS approaches. *Geoderma* **193–194:** 222–235.

Koehler, A.K., Murphy, K., Kiely, G. and Sottocornola, M., 2008. Seasonal variation of DOC concentration and annual loss of DOC from an Atlantic blanket bog in South-western Ireland. *Biogeochemistry* **95(2–3):** 231–242.

Lewis, C., Albertson, J., Xu, X. and Kiely, G., 2011. Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope. *Hydrological Processes* **26**(10): 1527–1537.

Lewis, C., Albertson, J., Zi, T., Xu, X. and Kiely, G., 2012. How does afforestation affect the hydrology of a blanket peatland? A modelling study. *Hydrological Processes* doi: 10.1002/hyp.9486

Liu, W., Xu, X. and Kiely, G., 2011. Spatial variability of remotely sensed soil moisture in a temperate-humid grassland catchment. *Ecohydrology* **5:** 668–676.

Xu, X., Kiely, G. and Lewis, C., 2009. Estimation and analysis of soil hydraulic properties through infiltration experiments: Comparison of BEST and DL fitting methods. *Soil Use and Management* **25:** 354–361.

Xu, X., Liu, W. and Kiely, G., 2011a. Modeling the change in soil organic carbon of grassland in response to climate change: Effects of measured versus modelled carbon pools for initializing the Rothamsted Carbon model. *Agriculture, Ecosystems & Environment* doi:10.1016/j.agee.2010.12.018.

Xu, X., Liu, W., Zhang, C. and Kiely, G., 2011b. Estimation of soil organic carbon stock and its spatial distribution in the Republic of Ireland. *Soil Use and Management* doi:10.1111/j.1475-2743.2011.00342.x.

Xu, X., Lewis, C., Liu, W., Albertson, J.D. and Kiely, G., 2012. Analysis of single-ring infiltrometer data: comparison of BEST and Wu methods. *Agricultural Water Management* **107:** 34–41.

Zhang, C.S., Tang, Y., Luo, L. and Xu, W.L., 2009. Outlier identification and visualization for Pb concentrations in urban soils and its implications for identification of potential contaminated land. *Environmental Pollution* **157:** 3083–3090.

Zhang, C., Tang, T., Xu, X. and Kiely, G., 2011. Towards spatial geochemical modeling: Use of geographical weighted regression for mapping soil organic carbon contents in Ireland. *Applied Geochemistry* **26(7):** 397–441.

Acronyms and Annotations

ANN	Artificial neural network
BEST	Beerkan Estimation of Soil Transfer Parameters
CFV	Coarse fraction volume
C4i	Community Climate Change Consortium for Ireland
CH_4	Methane
CLC	CORINE Land Cover
CO_2	Carbon dioxide
DEM	Digital elevation model
DOC	Dissolved organic carbon
EPA	Environmental Protection Agency
ER	Enrichment ratio
EU	European Union
GEOtop	A process-based rainfall/run-off model
GHG	Greenhouse gas
GIS	Geographic information system
GSI	The Geological Survey of Ireland
GWR	Geographically weighted regression
IFS	Irish Forest Service
K_s	Saturated hydraulic conductivity
K_{sc}	Compacted saturated hydraulic conductivity
LUC	Land use change
masl	Metres above sea level
N_2O	Nitrous oxide
NSD	National Soil Database
OM	Organic matter
POC	Particulate organic carbon
PSD	Particle size distribution
PTF	Pedotransfer function
RMSE	Root mean square error
RUSLE	Revised Universal Soil Loss Equation
SDR	Sediment delivery ratio
SEDD	Sediment delivery model

SEOF	Saturated excess overland flow
SHP	Soil hydraulic properties
SOC	Soil organic carbon
SOM	Soil organic matter
SRES	Special Report on Emissions Scenarios
SSC	Sand–silt–clay
SSY	Suspended solids (or sediment delivery) yield
UCC	University College Cork
USDA	United States Department of Agriculture
USLE	Universal soil loss equation
VGM	van Genuchten–Mualem formulation

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil, Pobal agus Rialtais Áitiúil.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail;
- scardadh dramhuisce;
- dumpáil mara.

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.

epa
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