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Thematic Area-Soils

Interactions of soil hydrology, land use and climate change and their impact on soil quality (SoilH)

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STRIVE SYNTHESIS Report

Prepared for the Environmental Protection Agency

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DISCLAIMER

The EPA STRIVE Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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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 in Ireland, the temperate perennially moist climate has the effect of maintaining and sustaining Irish soils: at elevated SOC levels; at high levels of porosity; and at lower levels of bulk density, than is the case in drier climates for similarly textured soils. We have found that 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 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^{-1} yr^{-1} and in-stream sediment yield at < 0.2 t ha^{-1} yr^{-1}, which is low by international comparison. However erosion levels will increase in the future, if the significant increases in animal stocking density occur as are called for in the Department of Agriculture Food and the Marine report Food Harvest 2020. Expected increases in frequency and magnitude of extreme weather events (e.g. storms and droughts) are also likely to increase erosion levels.
2. In this project we sampled 31 mineral soil locations (three depths: 0cm, 15cm and 30cm) 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 USDA soil textural triangle. We sampled for bulk density, porosity, % sand, %silt and %clay, %SOC and hydraulic conductivity and the van Genuchten water retention parameters. In estimating bulk density, we excluded the coarse fraction (> 2mm) as is the globally accepted standard for all soil research. We coupled our samples with those of our earlier EPA SoilC project 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 (www.pedosphere.ca). We 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. This is aided by the fact that 18% of the Irish landscape is covered in peat where the %SOC is ~45.

3. We carried out in-situ infiltration tests at all 31 mineral sites during the summers of 2008 and 2009 with the purpose of using the "BEST" method to estimate the saturated and unsaturated hydraulic conductivity. However, due to these two continuously wet summers, we were unable to estimate the unsaturated hydraulic conductivity and were only able to estimate the saturated hydraulic conductivity. With a variant of the "BEST" method (known as the "Wu" method) we were able to estimate the water retention parameters. Our estimates of saturated hydraulic conductivity ranged from lows of 2 cm/day to highs of ~ 2000 cm/day or a range of 3 orders of magnitude. The range of hydraulic conductivities measured varied with some other international studies (Schaap et al., 2000).
4. Erosion of soil organic carbon (SOC) which ends up in suspended sediment in streams is of the order of 10 kg ha^{-1} yr^{-1}. The SOC loss range is 2.5 to 4.5% of the in-stream sediment.
5. Carbon lost as dissolved organic carbon (DOC) in stream-flow ranges from ~10 kg ha^{-1} yr^{-1} to ~150 kg ha^{-1} yr^{-1}. Low levels are associated with catchments dominated with mineral soils, while the highest values are associated with stream in peatland catchments.
6. It was not possible to produce an hydraulic classification of Irish soils in accordance with the more widespread classifications of Schaap et al. (2000) or Clapp and Horneberger (1978) using simple textural divisions and pedotransfer functions. Our data did not show significant difference among the conventional textural classifications. Our aim was to identify a reliable classification that would maximize the difference in hydraulic properties between different textural classes but minimize the difference within each class. The Irish Forest Service (IFS) classification is suitable for Irish soils. Irish soils differ from soils in other climates, due to the high SOC content and the perennial wet climate. Therefore, we produced a quantifiable hydraulic classification similar to that of the IFS. The existing qualitative IFS classification cannot be used for hydrological modelling. However our quantitative extension of the IFS classification enables it to be used for hydraulic modelling purposes. Our quantitative IFS classification is:
    a. Deep well drained mineral soils; Ks ~ 166 ± 534 cm/day
    b. Shallow well drained mineral soils; Ks ~ 22 cm/day
    c. Deep poorly drained mineral; Ks ~ 7.8 ± 6.8 cm/day
    d. Poorly drained mineral with peaty topsoil; Ks ~ 3.1 cm/day
    e. Alluviums; Ks ~ 14.2 cm/day
    f. Peats; Ks ~ 1030 cm/day at bog centre and 1.03 cm/day at bog edge
7. We carried out detailed in-situ sampling at 14 locations within one pristine blanket peatland and 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. We found that the bulk density varied from 0.055 g/cc at the bog interior to 0.11 at the bog edge. We sampled peat profiles to depths of 5m and found no increase in bulk density with depth. We found that the saturated horizontal hydraulic conductivity was approximately twice that of the saturated vertical conductivity. The saturated conductivity ranged from ~1.03 cm/day at the edge to ~ 1030 cm/day at the bog centre or a difference of ~ 3 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 scale to estimate annual 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 to date. However, we 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 suggest 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-runoff model (at hourly scale) – GEOtop - with our 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 we could calibrate GEOtop at the catchment scale. Furthermore, GEOtop was most successful where the rainfall data was most precise, typically with hourly rain-gauges within the catchment. In contrast the RUSLE uses only annual total rainfall amounts. We used GEOtop to model the catchments: the Dripsey 15 km^2 grassland catchment; the 1 km^2 Glencar peatland catchment; and the 3 sub catchments (245, 881 and 1186 km^2) of the Munster Blackwater. We found that GEOtop modelled well the stream flow for all catchments. However we have no measurements of erosion or SOC loss for the Munster Blackwater to compare to our model results. The simulations show that as we move downstream onto the flatter catchment areas with wide (~2km) floodplains that the erosion increases. We consider that this increased downstream erosion is a product of increased areas of tillage and in particulate floodplains that suffer frequent flood events (several times each year), leaving mobile sediment on the riparian river banks readily available for transport downstream in the next flood. The only catchment that we had detailed suspended sediment yield (SSY) for was the Dripsey and GEOtop modelled the SSY of Dripsey very well. Using GEOtop we carried out a number of additional exercises:
    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. However, the current prevailing temperate climate factors and land use tend to mitigate the factors that work to cause compaction, keeping Irish bulk densities low and hydraulic conductivities high.
11. Surface sealing (e.g. urbanisation, suburbanisation and infrastructural developments) has increased significantly in Ireland in recent decades and was estimated (using data up to 2000) as ~1.6% of the total land area of the Republic of Ireland. This compares to an EU range of 0.15% (Iceland) to 13.7% (Malta). By comparison, the values for the UK are 3.3% and Germany 5.1%. However using data up to 2006, our updated estimate of surface sealing is ~ 2.1%. 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, 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 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, we found that 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 top soil (to a depth of approximately 20 cm) is considered reversible; and compaction at the lower depths to about 50 cm is considered to be 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 un-compacted soils. Compacted soils thus result in greater erosion and higher losses of organic matter than catchments with un-compacted 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 we examined the soil bulk densities at the 46 mineral soil locations of our EPA project SoilC which had taken soil samples to a depth of 50 cm, we found no evidence of compaction in the topsoil. 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 top soil samples were less than that estimated from textural analysis (% sand, silt and clay). We consider that this "under-compaction" is due to the loose porous nature of Irish mineral top soils 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 re-seeded every few years. Furthermore we found for all topsoils and lower depth soils (to 50cm) that the estimate of the soil porosity based on gravimetric data was higher than the porosity estimated from knowledge of texture only. However, we found only 2 of the 46 samples to be compacted at the deeper depth of 25 to 50 cm. These 2 sites were in arable land use.
14. In contrast to our EU neighbours, we find no evidence of widespread soil degradation across the sites we 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 soil organic carbon combined with the widespread land cover of grassland seems 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 with it problems of inadequate services (e.g. water, wastewater) and potential for increased urban and more frequent road infrastructure flooding. However, the 2.1% is low on the international scale. Our nearest neighbours are all at levels twice or more. Of the 136 landslides documented by the Geological Survey Ireland, 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 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 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 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.

Recommendations for future research:

1. Since there is no field experimental research in Ireland on erosion, loss of SOC and compaction, we recommend that the EPA address 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/runoff models (e.g. GEOtop) for Irish soils.
2. We recommend a small scale field and laboratory campaign to examine the methodology of bulk density determination. We know that bulk density determined by excluding the > 2mm fraction is correct for carbon stock measurement. However, for hydraulic studies, some suggest that the soil fraction > 2mm be included. We need to know if there are significant differences between the values of bulk density between the two methods.
3. We recommend the extension of the SoilH and Soil C 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 soil hydraulic properties and we recommend a national scale field campaign to determine the hydraulic properties of Irish soils on the scale of the 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, it is clear to the authors that these extremes may be the cause of much greater threats to soils that the threats

that were examined in this report. Land use change in Ireland over the century (particularly urban/suburban) suggests that more research about surface sealing impacts on hydrology and groundwater resources is required. We recommend the EPA to address rainfall extremes with consequent threats of flooding as a potential threat to soils.

7. There is a multiplicity of agencies in Ireland involved in and responsible for soil data, soil information and soil research. We recommend that a single national agency be the home of soils data, information and research. With the decommissioning of soil laboratories in Teagasc in recent years, we recommend that an agency like the EPA (and similar to JRC) be the national focus of soil research in Ireland.

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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 grassland is much higher than in most other counties in the EU, while the percentages of arable land and forestry are much lower. The Irish temperate climate has a mean annual temperature of ~10^{o}C (with a monthly range of ± 7^{o}C). The island average annual rainfall of ~1000mm (range 700mm to 1400mm) is wet but the intensity of rainfall is not severe. While Ireland can be described as "hilly", the highest mountains at 1000m are low relative to most other countries. The dominant grassland cover on lands with elevation mostly lower than 200m and a temperate rainfall suggests 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 which ranges from 0.15% to 14.7%.

Soils are a vital non-renewable resource that provides 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 has been a number of important initiatives: The *Thematic Strategy for Soil Protection* (CEC 2006) and the EU Soils Atlas (Jones et al., 2005). The Strategy 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 also compromise key soil functions. The Thematic Strategy 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 Objective

The aim of this research is to understand 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:

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. Use (2) to develop a hydrological classification of Irish soils
4. To identify a small number of representative Irish river catchments for river rainfall-runoff 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-runoff model GEOtop, and so enable hourly modelling of Irish river catchments of the three threats: erosion; loss of OM; and compaction.
6. Use GEOtop to examine future scenarios of land use and climate change on the threats to soils - erosion; loss of OM; and compaction.
7. Use RUSLE (for erosion) and SEDD (sediment delivery), in conjunction with GIS and spatially available datasets 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, use RUSLE and SEDD to examine the erosion and sediment delivery threats posed under possible future land use and climate changes scenarios
9. Use GIS and currently available data sets to update estimates of surface sealing (urbanisation/suburbanisation) in Ireland.
10. Use GIS and available data sets to develop a risk assessment tool for the threats of landslides
11. To write a final report, publish papers, a PhD thesis 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, we expect an increase in the frequency and duration of dry periods (droughts) as well as increasing precipitation amounts and intensity and extremes events (floods) in many areas of the world (IPCC 2000). Consequently, there are increased risks for landslides and soil erosion with implications for loss of organic matter. Climate change in Ireland is predicted to: incur an increase in temperature for all months of between 1.25 and 1.5 ℃; a decrease in summer precipitation (of ~ 10%); and an increase in winter precipitation (of ~ 15%) for the 2021-2060 period (McGrath et al., 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, this plan calls for an increase in the animal herds numbers (e.g. 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**.

Soil sealing - urbanisation and suburbanisation

In this project we address explicitly the first class of sealing, and leave the second class of sealing to be treated within the *soil compaction* analysis. A recent study from EU DG Environment (EEA 2012), examined the extent of urban surface sealing with: 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 a recent 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% of the year 2000. In 2000, of the total land area of the Republic of Ireland, Eaton et al (2008) estimated the suburban extent was 1.26% 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).

Soil compaction

Soil Science America (2006) 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 where 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 by the passage of animals. Common agricultural practices including tillage, fertilization 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). Organic matter helps to retain soil water thus enabling soils to rebound against compaction. Maintaining an adequate amount of OM in the soil stabilizes soil structure and resists degradation. It is considered that OM: binds soil mineral particles; reduces aggregate wettability; influences the mechanical strength of the soil aggregate (Hamza and Anderson, 2005).

Topsoil compaction occurs to a depth of approximately 20 to 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 tire or track. Reducing contact pressure causes 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 axel loads and may be irreversible. Axle loads greater than 5 tons 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 functions. 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 and 2006b). Soil compaction increases bulk density, which decreases the hydraulic conductivity, and induces earlier saturation levels (with regard to the water retention curve). The more the compaction there is, the greater the effects. The saturated hydraulic conductivity (K_s) is mostly determined by the amount of 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 (2006) suggested that the ratio of compacted saturated hydraulic conductivity (K_{sc}) to initial (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% SOC, such land use management is likely to experience 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.

Soil erosion

We define the terms, “erosion” and “sediment yield”. “Erosion” is the gross amount of soil detached from the land surface (e.g. grass field) with some fraction being re-attached to a downslope area of the catchment and the remainder being transported down the slopes into a catchment stream outlet. “Sediment yield” (SSY or SY) 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* which is still, in its revised form (RUSLE), the basis for determining erosion from "highly erodible lands" for various USDA programs.

The RUSLE equation is expressed as:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{1.1}$$

- 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. This amount is then compared to the “tolerable soil loss” limits or threshold to evaluate the soil loss severity.
- R is the rainfall-runoff erosivity factor which varies by geographic location. The greater the intensity and duration of the rain storm, the higher the erosion potential is.
- 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 metres 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 runoff. 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 meter 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 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 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.
- P is the support practice factor, the ratio of soil loss with a support practice like 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 runoff 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 reduces soil productivity. The study by Van Oost and Govers (2006) showed erosion rates in tillage land can exceed 10 t ha^{-1} yr^{-1}, 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 water courses, (Scanlon et al. 2005; Jordan 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 (SSY) from a nested set of small grassland catchments in Dripsey, County Cork where the SSY export ranged from 0.073 to 0.136 t ha^{-1} yr^{-1} for 2002. Harrington and Harrington (2011) measured the SSY from two rivers in the South West of Ireland and found SSY of 0.142 to 0.256 t ha^{-1} yr^{-1} 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), the total SSY exports were estimated from grassland agricultural land in 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 exports of between 0.127 and 0.24 t ha^{-1} yr^{-1} were estimated. If we assume that the mean SSY in these catchments was 0.2 t ha^{-1} yr^{-1} and further assume an SDR of ~0.5, then the erosion rates of these small grassland catchments was ~0.4 t ha^{-1} yr^{-1}. Verstraten and Posen (2001), found that the SSY export ranged from 0.50 to 26.0 t ha^{-1} yr^{-1} 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 to 20 t ha^{-1} yr^{-1} by comparison with the observed Irish magnitudes above of ~ 0.2 t ha^{-1} yr^{-1}. Land use **is clearly** most important control on erosion (Cerdan et al., 2010) with bare soil (tillage and vineyards) having highest erosion rates (3.6 to 17.4 t ha^{-1} yr^{-1}) and permanent vegetation (shrub, forest and grassland) having erosion rates less than 1 t ha^{-1} yr^{-1}.

Loss of soil organic matter (SOM)

In discussing the loss of *soil organic matter (SOM),* we can interchangeably discuss the loss *soil organic carbon (SOC),* as in general SOC ≈ 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. Soil organic matter (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% to 50% SOC; organic soils are defined as those with an SOC > 12% ; mineral soils contain SOC up to 12% SOC. Overuse of soils, as in intensive tillage practices tend 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 3 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 is seen as a measure of soil quality and productivity. Increasing SOC is considered desirable from an agricultural perspective and from a carbon sequestration perspective, the latter being considered as a GHG mitigation strategy. Jones et al (2005 a,b) 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 et al., (2012) note that in the EU-25 that most soils are out of C 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, that carbon stocks are generally in decline. In modelling studies of the loss of soil carbon, once the erosion loss is estimated, then the loss of SOC can be estimated by multiplying the erosion loss by an "*enrichment ratio*", typically about 3.5%. The SOC enrichment ratio (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 semiarid soils in India. Based on ten years of erosion data from the Woburn Erosion Reference Experiment, Bedfordshire, United Kingdom, 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^{-1} yr^{-1} 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^{-1} yr^{-1} from the blanket Peatland, which was strongly influenced by the high rainfall (~2500 mm yr^{-1}) in the catchment. The study in Ireland by Kiely et al. (2008) 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 stream was estimated to range from 11 to 156 kg C ha^{-1} yr^{-1}. The annual DOC exports were found to vary with land use class, with peatland catchments exporting three times that of arable (this was mainly due to the high runoff 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 percent of arable lands in the catchment increases, and DOC exports increase as the percent of peatland in the catchment increases. The type of soil drainage class (e.g. shallow well drained soils etc) 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), generalized that dissolved organic carbon concentrations in organo-mineral catchments seems 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 to 31.7 kg SOC ha^{-1} yr^{-1} for a number of arable plots in the UK. Kiely et al (2008) estimated for 55 Irish streams the loss of DOC as 11 to 156 kg C ha^{-1} yr^{-1} .

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, in areas with shallow topsoils, or associated with river erosion. Landslides in peat soils, however, are much more common in Ireland and Scotland (Creighton, 2006; Dykes, et al., 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 GSI published an inventory of Landslides in Ireland (Creighton, 2006), and the inventory in 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 synthesize a hydrological classification of Ireland's soils from various soil hydrological properties.

Soil hydraulic properties (SHP)

The soil hydraulic properties (SHP) of interest are:

- *soil water retention curve* and the
- *soil hydraulic conductivity* curve.

The *soil water retention curve* is the relationship between the water content, θ, (usually on horizontal axis) and the soil water potential, ψ. When a soil is saturated, the soil holds water via capillary forces and its potential is close to zero. When a soil is close to wilting point (or drought), the little amount of water that is in the soils is held tightly to the soil particle surfaces by adsorptive forces and its potential is high ~ 1.5MPa (~15hPa). 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 will involve mainly capillary binding, and will 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 relate to its saturated value. These soil hydraulic properties are a requisite for modelling rainfall/runoff, for modelling water and solute transport, managing irrigation and drainage problems, coupling precipitation and runoff in climate and hydrology models, for process based modelling of erosion and loss of organic matter and for 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). 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 soil hydrological properties have generated many semi-empirical and statistical equations (e.g. pedotransfer functions) describing the water retention curve (Kutilek and Nielsen, 1994). These equations contain parameters which, generally, have little if no direct physical meaning and are mainly used as fitting parameters to match a function to experimental data points. The most common parameterization of the hydraulic properties in mathematical models for flow and transport in porous media is now the van Genucthten –Mualem (VGM) formulation.

Classification of soil hydrological properties

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

$$\Psi = \Psi_s W^{-b} \tag{1.2}$$

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 Horneberger (1978) give representative values for Ψ_s, θ_s *and* b for each of 11 soil textures from sand, sandy loam to…silt, silty clays with their values based on experiments. Their power curve representing unsaturated hydraulic conductivity (K) is:

$$\mathrm{K} = \mathrm{K}_s W^{2b+3} \tag{1.3}$$

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 (Clapp and Horneberger, 1978), values for K_s are given for a range of 11 textural classes. While soil hydraulic properties have tended to rely on texture in determining a suitable PTF, a more simple soil hydraulic classification based on a drainage classification may be useful, such as: well drained; medium drained; imperfectly drained and poorly drained. Such a simpler classification might be appropriate, if more complex formulations might not be workable.

1.3.3 Rainfall-runoff modelling: GEOtop

Rainfall runoff models have proved to be a vital tool in many fields and provide solutions to many practical problems from 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 organic matter 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 is 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 process 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 dependent on 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 is to determine a hydraulic classification of Irish soils. The second task is to examine the threats to the sustainability of soil's 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 lands cover type and changes, the land management practices, the topography and climate. The study methodology included:

1. A field and laboratory study of soil properties including bulk density, SOC and soil hydraulic properties which we use 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 organic matter 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 GEOtop with a range of density values to determine the impact of compaction on runoff and erosion.
5. An examination of Irish soil surface sealing (urbanisation) in a desk study.
6. An examination of landslides using GIS to identify areas across Ireland at risk.

2.2 Measurements and estimation of soil hydraulic properties

2.2.1 Locations of soil sampling programme

For site selection for field tests, we collected field samples enabling the determination of the soil hydraulic properties of a range of soils, representing the land uses and their geographical spread throughout Ireland. As texture (sand, silt, and clay) is the first measure in understanding soil hydraulic properties, it was decided that soil texture (rather than soil type) should be a key criteria for the site selection. In order to utilise as much 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 1310 data points of the National soils Database (NSD) (EPA 2007, fay et al., 2007a, b) and from the 62 points of the SoilC (Measurement and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils (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 in the PhD thesis by Lewis (2011) and in the full 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 includes the soil hydraulic properties (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 the full SoilH report and in Lewis (20110. 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 SoilH samples	No of SoilC 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	11	18
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	32	38
Peat	18.37	1	21
TOTAL	100	32	59+

2.2.2 *Hydraulic properties, sampling, methods, and theory*

From a review of both in-field and laboratory methods for determining hydraulic properties, it was decided that the BEST (Beerkan Estimation of Soil Transfer Parameters) 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 datasets, 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 Wu method (Wu et al., 1999) was used in these cases.

Field infiltration experiments were carried out at 31 mineral soil sites at 3 different depths; the surface, 15 cm and 30 cm (Figure 2.1). These field tests were carried out in accordance with recommendations of Prof. Richard Cuenca of Oregon State University OR, USA, who provided us with the field experimental protocol (see Lewis, PhD thesis, 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.

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 3 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 then plotted and knowing the pre and post experiment soil moisture, the BEST method was then 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 or at saturation), the Wu method of analysis (Wu et al., 1999) was used.

Bulk density, particle size analysis and moisture content.

Bulk density samples were taken at three depths: the surface, 15 and 30 cm depths, using Eijkelkamp ART NR07010253 stainless steel bulking density sampling rings, (80mm diameter by 50mm high; volume 251. cc) (Eijkelkamp, Agrisearch Equipment BV, The Netherlands). The bulk density samples were taken before the infiltration experiments commenced at a distance of 20 to 25 cm away 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 the samples were oven dried at 105℃ for 24 hours and sieved to 2 mm. Bulk density (ρ) (g cc^{-1}) was estimated from eqn. 2.1.

Figure 2.1 Infiltration experiment at site # 180 with the infiltration experiment at surface in the foreground with 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.

$$\rho = \frac{M_d}{Sv - CFV} \tag{2.1}$$

where M_d is the dry mass (g) of the sample < 2 mm, S_v is the total sample volume (cc) and *CFV* is >2mm coarse fraction volume (cc). We excluded material greater than 2mm.

2.2.3 Peat soils sampling methods

Site description

The Glencar catchment is a pristine Atlantic blanket bog near Glencar in County Kerry, southwest Ireland (latitude 51 58′N, longitude 9 54′W) at an elevation of approximately 150 masl (meters above sea level) and is typical of Atlantic blanket bogs in the coastal regions of northwest Europe (Sottocornola et al., 2009). The depth of the bog varies from approximately 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 U.C.C.; see section www.hydromet.org for further details on the meteorological tower. The range of annual rainfall since 2002 was 2236 to 3365 mm with an estimated eddy covariance estimated evapotranspiration range of 369 to 424 mm and an average of 208 wet days (> 1 mm day^{-1}) per year. The average annual air temperature is 10.5℃. A small stream runs through the centre of the bog and drains approximately 76 ha, 85% of which is relatively intact blanket bog.

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. (2003a) 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 apart adjacent to the stream to 50 m apart at the bog interior.

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 this an Eijkelkamp 04.09 peat sampler (Eijkelkamp, Agrisearch Equipment BV, The Netherlands) for bulk density analysis was used. Using this auger which has a semi-circular 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 deep. These samples were placed in airtight bags for later laboratory analysis. The samples for bulk density (below 50 cm) were oven dried for one week at 55 ºC. Samples were then weighed and re-weighed 24 hours later to ensure 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 and the samples were then dried, and bulk density was estimated using eqn 2.2.

$$\rho_{bd} = \frac{m_d}{V_{or}} = \frac{m_d}{l * h * w} \qquad (2.2)$$

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.

$$\theta = \frac{m_{tot} - m_d}{m_{tot}} * 100 \tag{2.3}$$

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 full SoilH report.

2.3 Catchments descriptions for rainfall/runoff modelling

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

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	1470
Glencar	213-141	1.0	22	0.73	10	0	0	90	0	0	2571
Duarrigle	672-102	20	3.9	245	63.9	15.9	0.6	14.4	0.4	4.5	1456
Dromcummer	669-67	30	2.7	881	66.1	16.4	4.9	7.5	0.5	2.7	1356
Mallow	671-35?	45?	2.1?	1278?	63.5?	14?	12.6?	5.16?	0.9?	3.84?	1303

For rainfall-runoff, erosion and loss of OM analysis we focus on three catchments:

1) The Dripsey grassland;
2) The Glencar petland and
3) Three sub-catchments of the Munster Blackwater
    - Duarrrigle
    - Dromcummer and
    - Mallow.

2.4 GEOop - Rainfall/Runoff Model

GEOtop (Endrizzi et al., 2011; Rigon et al., 2006) is a distributed hydrological model and 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-runoff, 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 shortwave 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 focuses on impacts to soil resources (and not necessarily on channel integrity) only inter-rill and rill erosion were considered. Therefore only the effects of both *rain splash detachment* and *flow detachment* were considered. Splash detachment is the detachment of soil particles due to the impact of rain drops 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 Figure 2.2 (Boardman and Poesen, 2006).

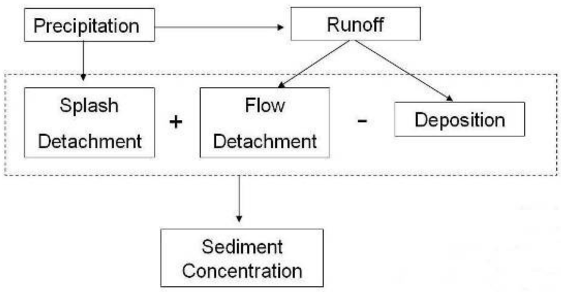

Figure 2.2. Flow chart of erosion processes (from a presentation by JD Albertson at the EPA-Soil H steering group meeting).

For the development of the erosion module in GEOtop, the LISEM model (DeRoo et al., 1996) was adopted and we developed a new module in GEOtop for the online calculation of distributed erosion, sediment transport, and deposition rates. The LISEM model (DeRoo et al., 1996) is a physical based erosion model that runs at the event and catchment scale. The original LISEM model runs in a GIS environment and modelled erosion is comprised of splash detachment and flow detachment from over land flow in rills.

2.4.2 GEOtop - New Soil Organic Carbon Loss Module

We have incorporated a soil organic carbon (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, and it considers SOC loss in two separate ways; the particulate organic carbon (POC) loss and leaching of dissolved organic carbon (DOC).

$$\frac{dSOC}{dt} = litter - R - POC - DOC \quad (2.4)$$

$$POC = SEro * pocc * enrichment \qquad (2.5)$$

where SEro is the rate of soil mass loss due to erosion (g m^{-3} d^{-1}); pocc is the concentration of soil particle organic carbon; and enrichment is the enrichment factor. The leaching rate of DOC to be estimated by eqn. 2.6.

$$DOC = docc * q * A \qquad (2.6)$$

Where $docc$ = dissolved organic carbon concentration in flows (g C m^{-3} d^{-1}); q (l s^{-1}) 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.

2.4.3 GEOtop –Soil Compaction

To examine if any of the soils sampled in this project were compacted, we compare the bulk densities of each site (plus the sites in the EPA SoilC project) based on the percentage sand, silt and clay with the actual measured bulk densities. We report the results in Chapter 3. We used functions developed by Assouline (2006a, 2006b). Compaction increases the bulk density and the ratio of compacted to initial bulk density is eqn. 2.7:

$$\frac{\rho_c}{\rho} \geq 1 \qquad (2.7)$$

Assouline (2006a) equations for the compacted saturated hydraulic conductivity, and defined the ratio of compacted saturated hydraulic conductivity to initial as eqn. 2.8:

$$\frac{K_{sc}}{K_s} = \left(\frac{\phi_c}{\phi}\right)^3 \left(\frac{\rho_c}{\rho}\right)^{\delta-7} \qquad (2.8)$$

Where $\left(\frac{\phi_c}{\phi}\right)$ is the ratio of compacted to initial porosity, and $\delta = 2$ for loamy soils.

In a similar way we adopt the methods for the water retention curve parameters 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, cm^{-1}) and μ (a shape parameter). Assouline (2006b) gives us the following equations, 2.9, 2.10.

$$\left(\frac{\alpha_c}{\alpha}\right) = \left(\frac{\rho_c}{\rho}\right)^{3.72} \qquad (2.9)$$

$$\left(\frac{\mu_c}{\mu}\right)=\left(\frac{\rho_c}{\rho}\right)^{\omega} \tag{2.10}$$

Where ω is ~1.0.

2.5 Empirical Erosion (RUSLE) and Sediment Delivery (SEDD) models

The equation of RUSLE is 2.11,

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{2.11}$$

where A is computed 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 a sediment delivery ratio (SDR) from the Sediment Delivery Distributed Model (SEDD). See Full SoilH report 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 2000. The IPCC Third Assessment Report (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 spilt up into 4 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 greenhouse gas 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 summarized in Nakicenovic et al., (2000): In Table 2.3 and 2.4 we present the climate change and land use scenario examined in this project. The future scenario simulations is based on the Special Report on Emissions Scenarios (SRES) A1B Scenario ((Nakicenovic et al., 2000) and the generalised results from C4i (McGrath et al., 2008). The percentage differences are from the current baseline of the 1961-2000 record.

Table 2.3. Climate Change Scenario (2021-2060)

Month	Jan, Feb, March, April	May, June, July, Aug	Sept, Oct, Nov, Dec.
Rainfall	+15%	-10%	+15%
Temperature	+1.25^{o}C	+1.25^{o}C	+1.25^{o}C

Table 2.4. Land Use Change Scenarios.

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

3. Summary Results of Field Soils Experiments

3.1 Introduction

To examine the threats to Irish soils, of erosion, loss of organic matter and compaction, we require a modelling capability to extend point information to the scale of the catchment. Our development to the rainfall/runoff model – GEOtop- enables us to use point and catchment scale data as input to examine time series (e.g. increments of 1 hour) catchment scale outputs of erosion and loss of OM and compaction. Our combination of GIS (and catchment scale data products, e.g topography) and the empirical erosion models – RUSLE and SEDD – enables us to estimate *annual* scale erosion and sediment delivery at the catchment and national scale. We exploit GIS techniques to examine surface sealing (urbanisation/suburbanisation) and landslides using available data products from the EPA, GSI and others. The soil properties that we quantify are:

1. Land cover
2. Soil type (Great Soil Group, e.g. brown podsols)
3. Physical
    a. %sand, % silt, % clay
    b. Bulk density
    c. Porosity
    d. USDA soil triangle classification (loam etc)
    e. Gradation
4. Chemical
    a. Soil Organic Content (%)
5. Hydraulic
    a. Hydraulic conductivity (unsaturated and saturated)
    b. Soil Water Retention characteristics (α - Scale parameter)

3.2 Mineral soils

We analysed soil samples 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 full SoilH report.

3.2.2 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 full SoilH report. From Table 2.1 (this report), we note that from the Gardiner and Radford (1980) classification and in our soil sample set, 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 respectively). ***Loam is considered ideal for agricultural uses because it retains nutrients well and retains water while still allowing excess water to drain away***.

3.2.3 Soil Classification – USDA

The 31 mineral soil locations were sampled for three replicates and at three depths (the surface, at 15 cm and at 30cm). In total we analysed 279 unique soil samples. The USDA classification of the 279 samples is shown in the USDA soil classification triangle (Figure 3.1). Most of our samples 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).

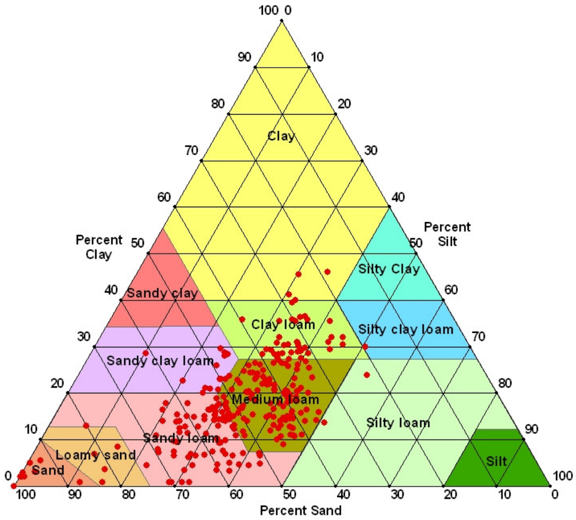

Figure 3.1 PSDs 31 mineral sites on the USDA soil classification triangle. The concentration of sites is in the medium-sandy loam region.

3.2.4 Bulk density and porosity of Mineral Soils

The bulk density and porosity of the mineral soil samples are included in Table 3.4 (full SoilH 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 (< 2mm) bulk density is defined as the dry weight divided by its volume, expressed in g/cc. Bulk density is dependent on soil texture, % sand, % silt, % clay, the SOC, and the soil packing. Assuming that most rocks have a bulk density of 2.65 g/cc, then a medium textured soil with 50% porosity has a bulk density of ~ 1.33 g/cc. 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/cc. 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 that the surface layers. Porosity is normally calculated from eqn. 3.1.

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

3.2.5 Gradation of mineral soils

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

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3.2.6 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 (*Ks*) and van Genuchten water retention parameter (α) partitioned into 8 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 (cm3/cm3), and a mean value of ~ 0.38.

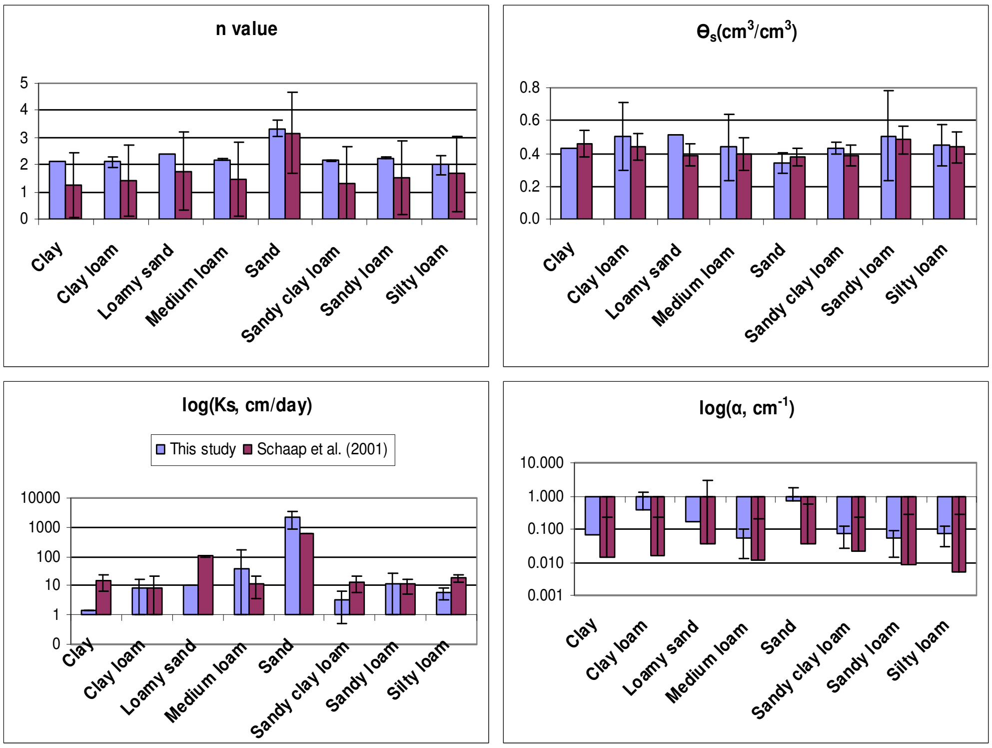

Figure 3.2. Soil hydraulic properties by texture. Our results vs Schaap et al (2000).

These values are very similar to Schaap et al (2000) and Clapp and Horneberger (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 class. All classes shown in Figure 3.2, show our *n* value ~ 2.0 except for sand which has an *n* value of >3. The *n* values from Schaap et al (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 our results are ~ 0.1 cm^{-1} while those of Schaap et al (2000) are closer to 0.01 cm^{-1} and Kutilek and Nielsen (1994) note a range of 0.01 to 0.001 cm^{-1}. α is considered as a measure of the inverse of the air entry potential (at saturation), cm^{-1}. 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 et al (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 3 orders of magnitude. For clays our *Ks* values are ~ 2 cm/day, compared to Clapp and Horneberger (1978) of ~25 cm/day and Schaap et al (2000) of ~20 cm/day. For medium loams (where most of our soil samples are concentrated) our *Ks* values are ~ 30 cm/day, compared to Clapp and Horneberger (1978) of ~60 cm/day and Schaap et al (2000) of ~110 cm/day. For sands our *Ks* values are ~ 2000 cm/day, compared to Clapp and Horneberger (1978) of ~1500 cm/day and Schaap et al (2000) of ~180 cm/day. Compared to the well-known separate data sets presented by Schaap et al (2000) and Clapp and Horneberger (1978) our values are somewhat different. It may reflect the fact that soil hydraulic properties have high spatial variation in nature, and different methods often produce high difference in values of same soil hydraulic properties. We also find that the sand class seems very different in soil physical and hydraulic properties from other texture classes (for our dataset and that of Schaap et al (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, we present results on two key variables: bulk density (ρ_d), 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/cc to highs of 0.79 g/cc . 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. We found that the bulk density Glencar decreased with increasing distance from the boundaries (e.g. stream). At the interior of the bog the bulk density was 0.055g/cc 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 (winter time), 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 our 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. (2011), Tomlinson and Davidson (2000) and others for peatlands with depths greater than 2 m (see Table 3.2 in the full SoilH report)

3.3.2. Peat soils – saturated hydraulic conductivity

Both the K_{hsat} (horizontal) and K_{vsat} 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^{-1} near the stream to ~10^{-4} m s^{-1} at the bog interior, a difference of three orders of magnitude. K_{vsat} for the near-surface depth ranged from ~10^{-6} m s^{-1} near the stream to ~10^{-4} m s^{-1} at the bog centre. K_{hsat} for the sub-surface depth (30 – 40 cm) ranged from ~10^{-6} m s^{-1} near the stream to ~10^{-4} m s^{-1} at the bog centre. K_{vsat} for the sub-surface depth ranged from ~10^{-6} near the stream to ~10^{-5} m s^{-1} at the bog centre. We found that anisotropy does exist with horizontal hydraulic conductivity approximately twice that of the vertical hydraulic conductivity. Our values of saturated hydraulic conductivity compare with others, including Beckwith et al. (2003a) who used the modified cube method in Thorne Moors, UK (raised bog), that we used., and found that the vertical hydraulic conductivity near the surface ranged from 10^{-3} to $1.6*10^{-5}$ m s^{-1} and horizontal hydraulic conductivity ranged from $8*10^{-4}$ to $1.6*10^{-5}$ m s^{-1}. Beckwith et al. (2003a) also reported vertical conductivity values at depths of 30 cm that ranged from $3.2*10^{-7}$ to $7.9*10^{-7}$ m s^{-1} and horizontal conductivity values at the same location that ranged from $2.5*10^{-6}$ to 10^{-5} m s^{-1}. 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). We 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 to 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 us 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 examine if there was evidence of compaction of Irish soils, we examined the 46 mineral soil sites of the EPA SoilC project. We use the sites from SoilC 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. We present the bulk density data for three depths: 0 to 10 cm; 10 to 25 cm; and 25 to 50cm. In Table 3.5 of the full SoilH report, we present two columns of bulk density: the first (column 8) is that bulk density determined by our gravimetric methods; the second (column 9) is the bulk density estimated from the textural analysis. The latter is estimated based on the methods described in www.pedosphere.ca and in Saxton et al, (1986). Comparing the gravimetric (*actual*) bulk densities of column 8 and 9 (*estimated from textural analysis*) we note that the measured gravimetric bulk density is frequently less than the textural analysis estimate. This suggests that in most sites examined, that there is little compaction. We consider that this apparent if not real “under-compaction” is due to the loose porous nature of Irish mineral top soils which are rich in organic matter (>3% SOC) and are perennially well watered. These factors mitigate against compaction. However, there may be issues with the way bulk density is measured. It is standard practice to exclude >2mm size particles when bulk density is required in determining soil carbon stocks. It may be appropriate to measure bulk density twice: once excluding > 2mm size particles; and once including the 2mm size particles. It would be relevant to determine if the bulk densities in both methods of measurement is 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 soil data on its physical, chemical and biological properties. Some of these properties are a function of soil type or texture. In others words, they may not change from region to region and are sometimes considered to be constant. However, many soil properties are not constant and are dynamic, responding to external influences of climate, land use or land use change. While we can use textural analysis (% sand, % silt and % clay) 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 also 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, there has been much effort applied in developing mathematical and statistical relationships between conventional soils data (e.g. texture) and soil hydraulic properties. These relationships are called *pedotransfer functions* (PTF) which emphasize the link between soil survey ("pedology") and soil hydrology, Pachepsky and Rawls (2004). In modelling work (e.g. rainfall – runoff), modelling related soil hydraulic properties are required. Statistical regression is the traditional tool of PTF's but artificial neural networks (ANN) are now proving attractive because of their ability to model complex systems and to be able to exploit data sets into "training" and "validation" sets. Particle size distribution and its parameters are used in many PTF's. The non-linearity in soil hydraulic properties 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 to 10 hours to complete. 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 full SoilH report, with Figure 3. containing a summary of the results from the particle size distribution 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. The van Genuchten parameters *α,* m and *n* are used to establish the water retention curve. The results of each infiltration experiment are given in in Lewis (2011).

4.3 Hydraulic Classification of Irish Soils

We examined two possible hydraulic classification schemes:

The first scheme was based on the 44 soil profiles from Gardiner and Radford (1980). For each profile, we used the % sand, % silt & % clay content (SSC), SOC, and the spatial distribution map and created pedo-transfer functions (PTF) to relate the existing *soil properties* (e.g. SSC) to *new hydrological soil properties,* (e.g. soil water retention shape parameter (*n*), soil porosity (*Φ*), *Ks*, and van Genuchten water retention parameter (α)). From our dataset, we developed a robust function to estimate bulk density from SOC (Figure 4.1a) and eqn. 4.1

$$BD = 1.39 - 0.312 Ln(\% SOC) \quad (4.1)$$

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

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

$$x_1 = 24.547 - 0.238 sand - 0.082 clay \quad (4.2a)$$

$$x_2 = -3.569 + 0.081 sand \quad (4.2b)$$

$$x_3 = 0.694 - 0.024 sand + 0.048 clay \quad (4.2c)$$

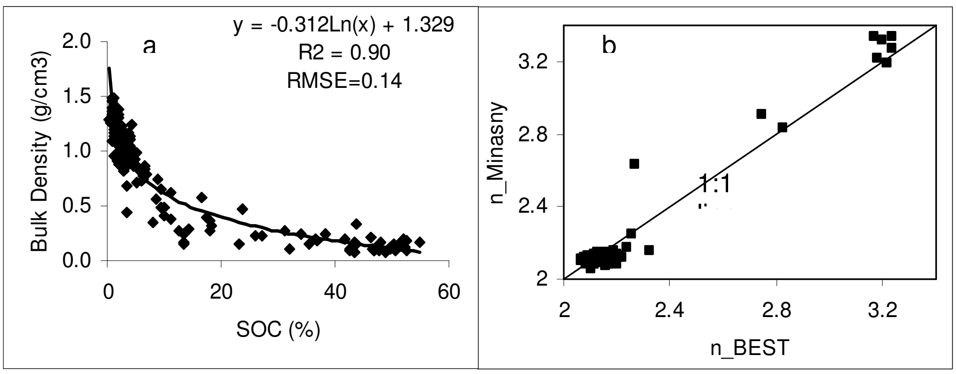

Figure 4.1. Relationships (a) between bulk density and SOC, and (b) between the Minasny estimated *n* and BEST estimated *n*.

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

The second scheme (Figure 4.2) is based on the existing Irish Forest Service (IFS) soil databases. There exists some hydrological classifications in the IFS database (e.g. deep well drained mineral etc); therefore we calibrated and adjusted some of the existing IFS classes with our own database (SoilH).

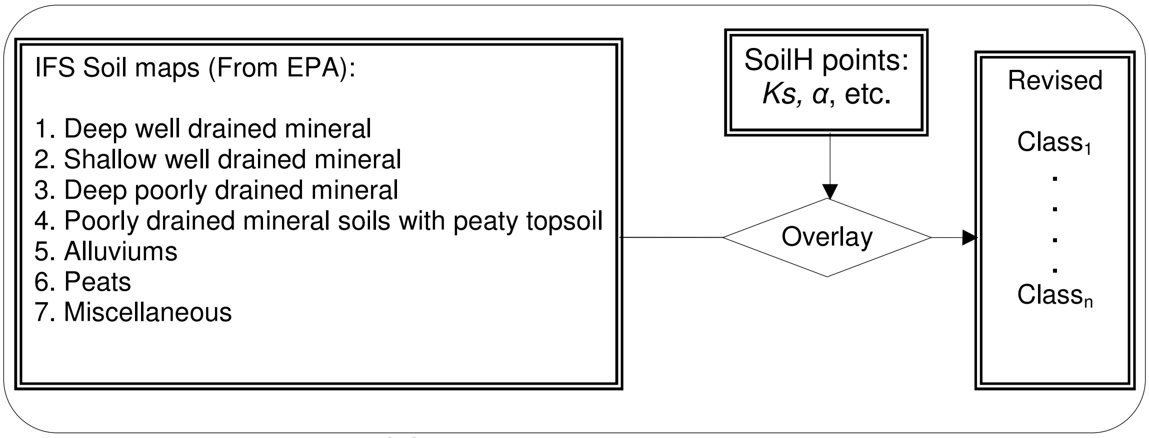

Figure 4.2. IFS Scheme for soil hydrological classification**.**

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 soil hydraulic properties (*Ks* and *α*) and readily measurable soil properties (% sand, silt, clay), the second classification scheme (Figure 4.2) was examined. The Irish Forest Service (IFS) soil database from the EPA (produced from the project of Soils and Subsoils data generated by Teagasc with co-operation of the Forest Service, the EPA and the GSI, Project completed May 2006) has 7 classes (Table 4.1) with spatial distribution shown in Figure 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 our 31 mineral sites were compared to the soil groups of the IFS soil database. From our 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. Our selected sites contained 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 fifth category (alluviums) each representing just over 3% contain one site each.

Table 4.1 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
Alluviums	5	3.55
Peats	6	29.1
Miscellaneous	7	3.28

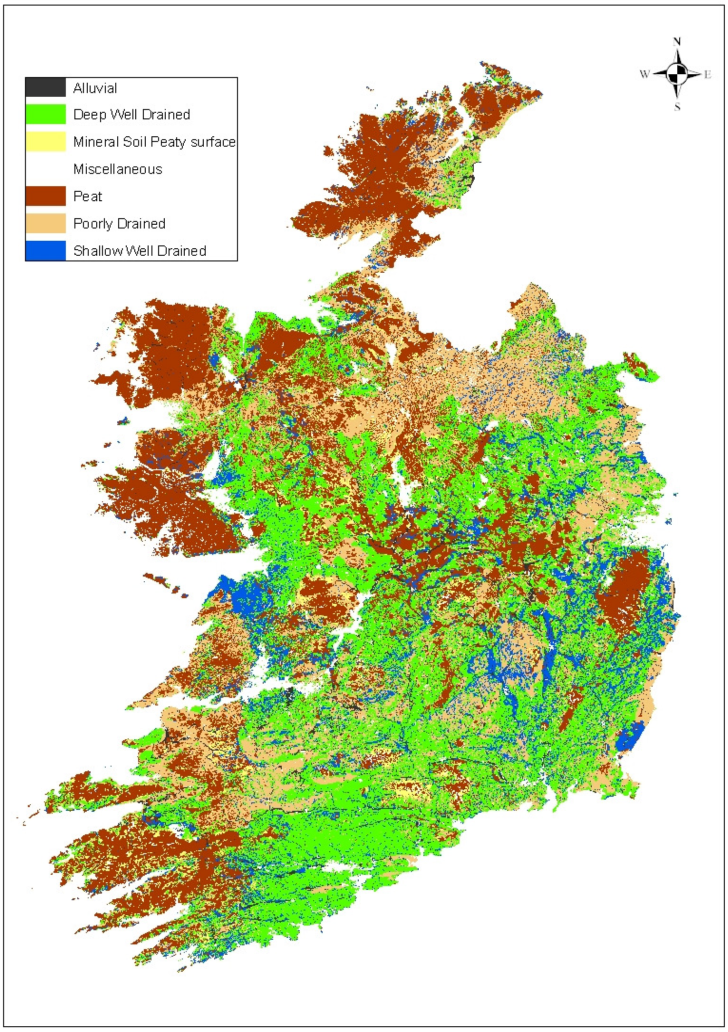

Figure 4.3 Distribution across Ireland of the IFS Soil Classes.

Table 4.2 Soil hydrological properties for 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 (cm^{-1})	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	1017.9 ±2712.6
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
Alluviums.	5	1	2.16	0.75	14.2	0.09	54.4
Peats.	6	1 bog centre 1 bog edge	-	-	1030 1.03	-	-
Miscellaneous.	7	0					

We show in Table 4.2 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; max 249; min 0.35; m $s^{-1}*10^{-6}$) with the K_s of poorly drained mineral sites two orders of magnitude lower (average 0.89; max 2.4; min 0.24 m $s^{-1}*10^{-6}$). Excluding the peat soils and alluvium, estimates of θ_S were between 0.36 and 0.46 (l l^{-1}). The highest values of the van Genuchten (1980) parameter α were observed (0.16 cm^{-1}) in deep well drained mineral soils (0.16 cm^{-1}), with the lowest α in deep poorly drained mineral soils (0.06 cm^{-1}). The van Genuchten (1980) parameter n ranged from 1.99 to 2.28.

4.5 Summary of Hydrological classification of Irish soils

As the existing classification in the IFS soil database is able to capture the differences in the saturated hydraulic conductivity (K_{sat}) and steady infiltration rate between well drained and poorly drained classes (Figure 4.4). So we propose to retain this IFS classification. It is important to note that the *existing* IFS *qualitative* classes CANNOT be used for hydrological models. We therefore *quantify* these classes (see Table 4.2), based on our available datasets of hydraulic properties from this project (SoilH). This updated quantitative information on soil hydrological properties for these classes can NOW be used in hydrological models (e.g. GEOTop).

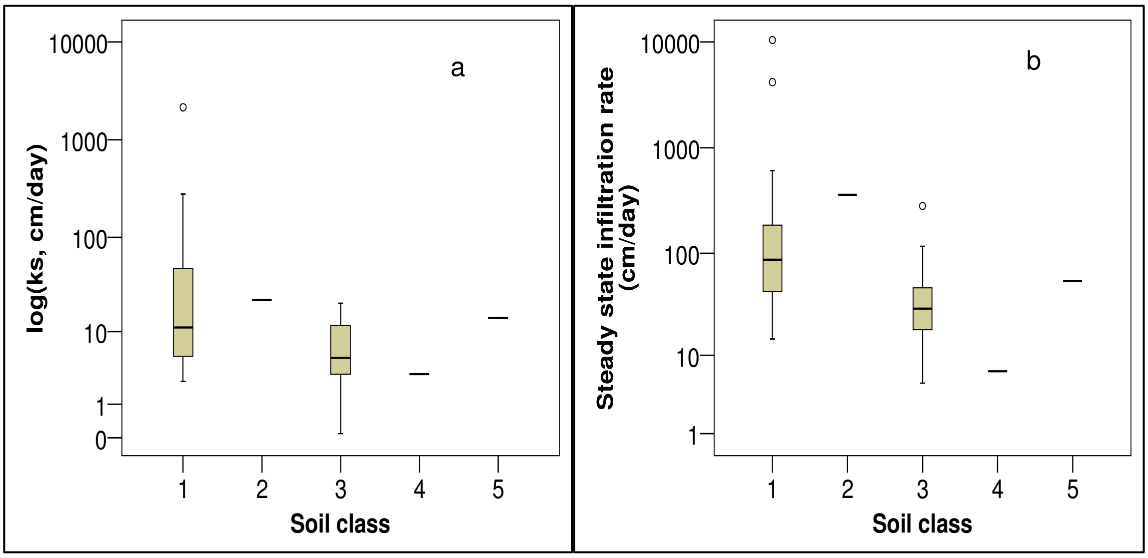

Figure 4.4. (a) saturated hydraulic conductivity and (b) steady state infiltration rate for each new SoilH class.

5. GEOtop Results

The GEOtop process based rainfall/runoff model with our 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 was input with topography, and the spatial distribution of soils and land cover at a pixel size of ~100m by 100m. For each catchment we had time series of observed river flow at 30 minute intervals for a number of years. In *calibration mode* we ran GEOtop for one year, *calibrating* some of the parameters which were not known to us (i.e. soil hydrological parameters including hydraulic conductivity). Once the model gave satisfactory results for stream flow (and water balance) we accepted the calibrated parameter set. We then ran the model in *validation mode*, with a different year of input data and without changing any of the prior calibrated parameters. The measure of how good the model performs is in how well the modelled river flow compares with the observed times series flow during validation.

5.1 GEOtop – Dripsey catchment

For the 15km^2 Dripsey grassland catchment, we used the year 2002 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 Suspended Solids Yield

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 flow for the validation year 2003. The rainfall for 2003 was 1198 mm. The simulated and observed annual flow was 774 mm and 695 mm, respectively. The residual estimate of ET was 503 mm.

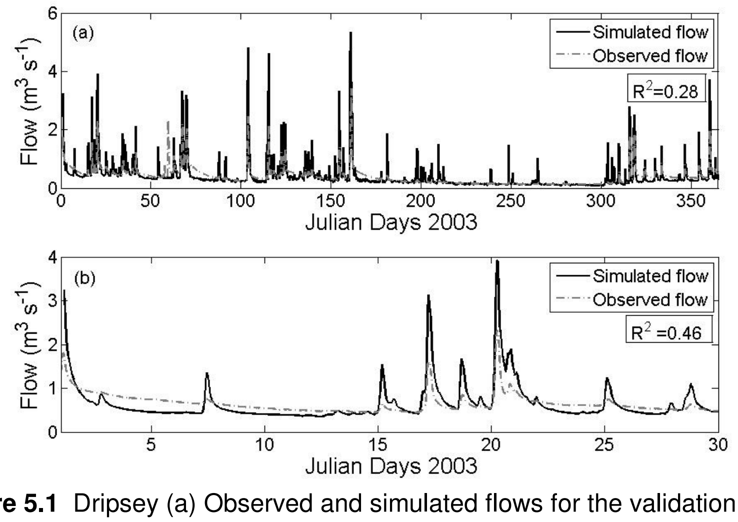

Figure 5.1 Dripsey (a) Observed and simulated flows for the validation year 2003, and (b) observed and simulated flows for the first 30 days of 2003.

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The results of the simulated and the observed suspended solids yield (SSY) are presented in Figure 5.2 for the validation year (2003). It is relevant to note that the flow proportional sampling of SS covered 42% of the 2002 year. For 2002, the simulated SSY was 0.159 t ha^{-1} while the observed SSY was slightly lower at 0.136 t ha^{-1}. Most "erosion" of 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 accurate, as the observed only sampled for 42% of the year, and the measured may have missed pulses during non-sampling periods. For the validation year 2003, we present the SSY results in Figure 5.2. The model estimates of SSY at 0.053 t ha^{-1} was lower than the observed SSY of 0.092 t ha^{-1}. It is relevant to note that the flow proportional sampling of SS covered only 21% of 2003 or half the frequency of 2002. Furthermore 2003 had only 774 mmm of stream flow by comparison with 1268 mm in 2002. Hence it is likely that the "observed" SSY might have been overestimated in the gapfilling method due to the lower frequency of SS measurements.

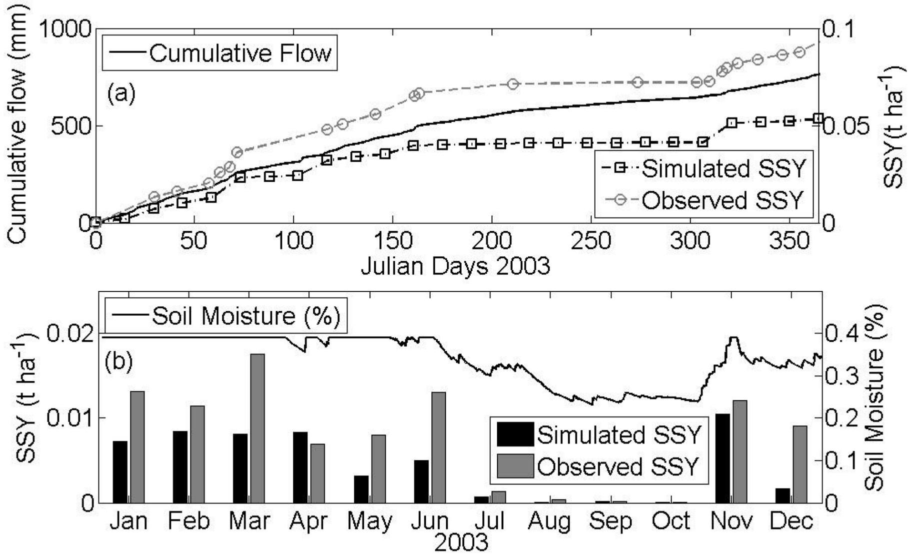

Figure 5.2 Dripsey (a) Observed and simulated SSY for the Validation year 2003; (b) monthly totals of simulated SSY, observed SSY and catchment average soil moisture content.

Figure 5.2b show 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 to September tended to have lower soil moisture for both 2002 and 2003 while November to 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. We note (in Tables in the full SoilH report), that 2002 had rainfall of 1822mm and 2003 had rainfall of 1180mm. 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 C ha^{-1} yr^{-1}. Assuming an SDR factor of 0.4 then the erosion ranges from 159 to 397 kg C $ha^{-1}yr^{-1}$. Assuming an enrichment factor of 3.5% then the SOC lost, ranged from to 6 to 14 kg C $ha^{-1}yr^{-1}$ or of the order of 10kg C/ha/yr.

5.1.3 Dripsey – GEOtop compaction modelling study

In Table 5.1 we present the results of the GEOtop compaction modelling scenario for the 15km^2 Dripsey grassland catchment. We have three cases:

(1) no compaction;
(2) increase bulk density by 10%; decrease saturated hydraulic conductivity by 50% and altered water retention curve parameters as per Assouline (2006).
(3) increase bulk density by 20%, decrease saturated hydraulic conductivity by 80% and altered water retention curve parameters according to Assoiline (2006).

For the modelling exercise we keep the rainfall (year 2006) 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 Figure 5.3). The major result is that with increasing compaction, erosion does increase as does the loss of SOC. This verifies the usefulness of GEOtop, for modelling flow, erosion and SSY.

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

	NO COMPACTION				**10% COMPACTION**				**20% COMPACTION**			
Month	**Rain mm**	**Flow mm**	**Erosion t/ha**	**SOC tC/ha**	**Rain (mm)**	**Flow (mm)**	**Erosion t/ha**	**SOC t/Cha**	**Rain (mm)**	**Flow (mm)**	**Erosion t/ha**	**SOC tC/ha**
Jan	286.5	151.4	0.025	0.0079	286.47	138.23	0.0704	0.0088	286.47	132.47	0.201	0.0096
Feb	114.9	188	0.041	0.011	114.87	182.51	0.1348	0.0125	114.87	180.63	0.279	0.0135
Mar	237.1	92.7	0.007	0.004	237.11	76.429	0.0156	0.0042	237.11	64.047	0.044	0.0042
Apr	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
Jun	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
Aug	41.5	38	0.0005	0.0007	41.525	33.397	0.0010	0.0010	41.525	22.013	0.001	0.0009
Sept	214.2	25.7	0.0002	0.00035	214.22	24.054	0.0004	0.0006	214.22	14.95	0.001	0.0005
Oct	173	76.1	0.017	0.0026	173	107.42	0.0495	0.0055	173	137.58	0.145	0.0091
Nov	132.13	164	0.024	0.0082	132.13	184.27	0.0622	0.0118	132.13	206.97	0.252	0.0153
Dec	258	162.8	0.0247	0.0087	258	160.93	0.0602	0.0105	258	163.04	0.214	0.0120
SUM	**1823.2**	**1185.4**	**0.152**	**0.054**	**1823.1**	**1169.5**	**0.4304**	**0.0685**	**1823.1**	**1160.3**	**1.248**	**0.0808**

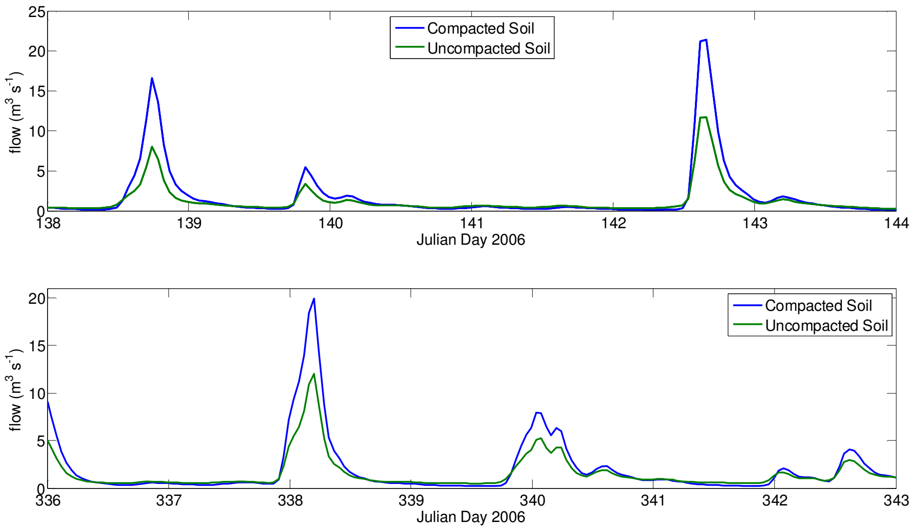

Figure 5.3 GEOtop simulations of compaction on river runoff for the 15 km^2 Dripsey catchment for parts of 2006. The green lines represent the time series of flow for the uncompacted (or as is) conditions. The blue line represents the compacted conditions based on a 20% increase in bulk density and an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

5.2 GEOtop – Glencar peatland catchment

For this peatland catchment our interests are in stream flow and DOC export.. We used the same methodology with GEOtop as we did with the Dripsey catchment. We used data for 2007 as our calibration year and 2008 as the validation year. We show the time series of observed and modelled flows for the validation year of 2008 (Figures 5.4, 5.5) and the model is seen to perform reasonably well. In Table 5.2 we summarise the results of GEOtop for 2007 and 2008. It is interesting to note that the runoff/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 almost identical R^2. In Figure 5.6 we show the time series of observed and modelled WT. Again the model results are very satisfactory with the model within a few cm of the observations. We note that the observed WT is only at one point in the catchment while the modelled WT level is representative of the total catchment

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)	Runoff/ rainfall ratio
Observed	2007	2229	304	1925	0.75
Calibrated Model	2007	2229	211	2018	0.82
Observed	2008	2826	421	2405	0.85
Validated Model	2008	2826	330	2496	0.88

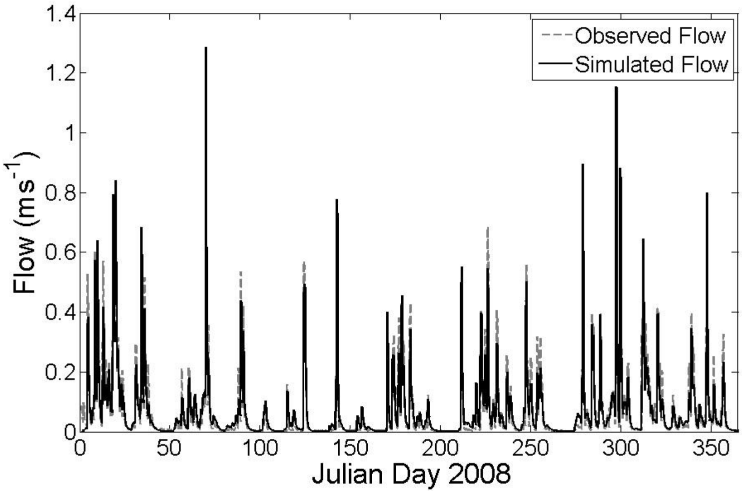

Figure 5.4 Observed and Simulated flows for validation year 2008 at hourly intervals.

In Figures 5.7 we show the measured daily stream discharge (m^3s^{-1}) and the mean daily concentration of DOC (mgl^{-1}) for the years 2007 and 2008. The two clear trends are that the DOC concentration increases in the summer (with increasing temperature) and the DOC concentration also increases (but less so) with increasing flow rate. When the DOC increases with flow, the DOC remains elevated for the next few days. In Figure 5.8 we show the cumulative stream discharge (mm) and the cumulative DOC export (kg C ha^{-1}). The DOC export increases in unison with increasing flow rate. As the DOC export is the product of stream discharge and DOC concentration (normalized 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 “jumps” in DOC export in Figure 5.8.

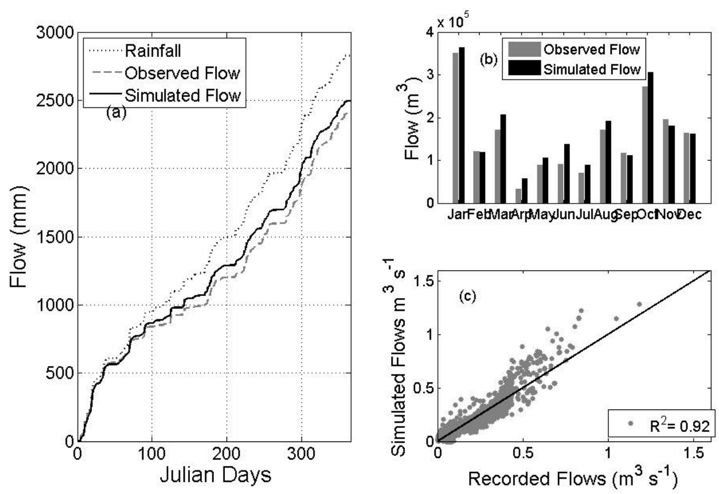

Figure 5.5 For 2008: (a) Cumulative rainfall, observed flow and simulated flow; (b) Monthly observed and simulated flows; (c) Observed and simulated flows.

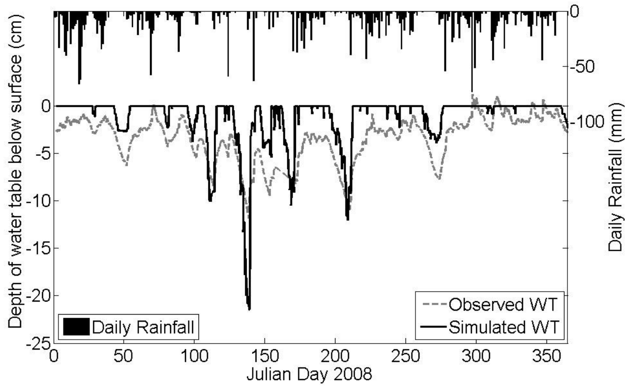

Figure 5.6 For 2008, daily rainfall (top); observed and simulated water table depth.

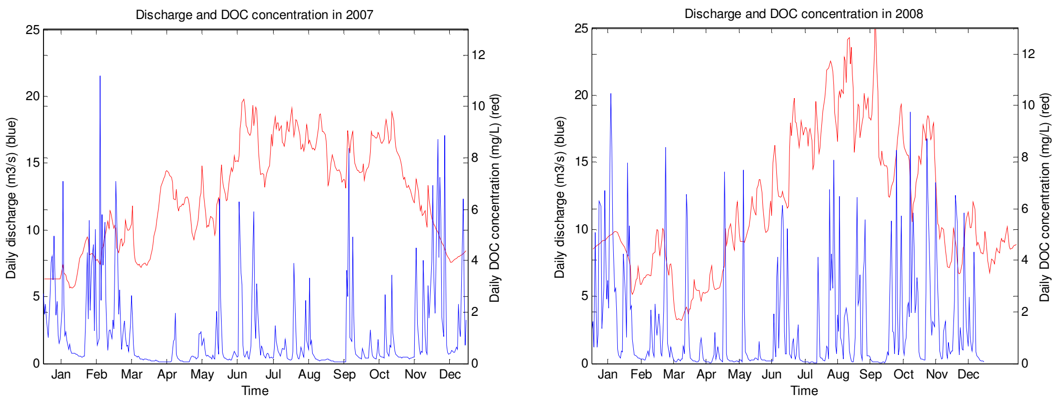

Figure 5.7 For 2007 and 2008, observed daily stream discharge (blue) and daily DOC concentration (mg/l).

In the full report we show Tables of monthly modelled output for 2007 and 2008 at Glencar. The modelled flows are similar to the measured. The DOC exported is similar to the measured. In 2007 the measured DOC export was 0.119 tC/ha by comparison with the modelled values of 0.106 tC/ha. In 2008 the measured DOC export was 0.150 tC/ha and the modelled values of 0.131 tC/ha.

5.3 GEOtop – Munster Blackwater – 3 sub- catchments

For 2006, we show in the full report 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. We show that the model simulates the river flow reasonable well for the three sub-catchments.

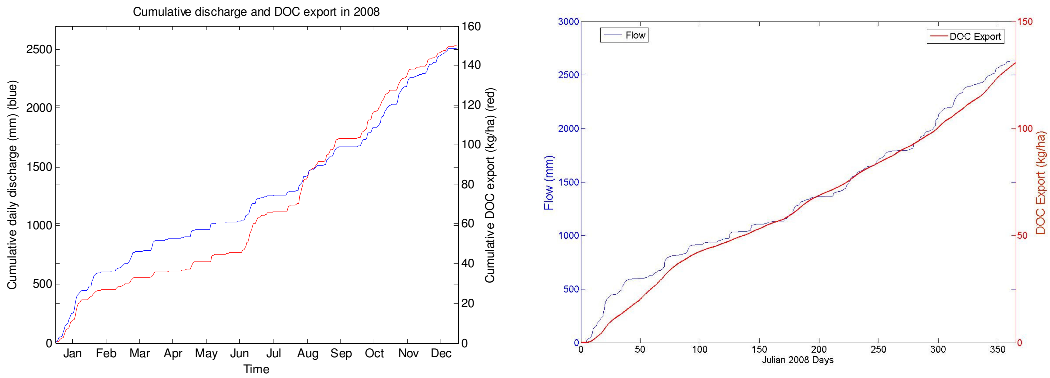

Figure 5.8 2008 (a) observed (b) modelled cumulative discharge (mm –blue line) and DOC export (kg/ha – red line)

GEOtop simulations for Land Use and Climate Change.

We carried out hypothetical scenarios of land use and climate change in accordance with Table 5.3 and Table 5.4 using GEOtop and the Duarrigle catchment. We present the results in Table 5.5 which show that while there is an increase in erosion (SSY) and loss of 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%.

Table 5.3. Climate Change Scenario (2021-2060)

Month	Jan, Feb, March, April	May, June, July, Aug	Sept, Oct, Nov, Dec.
Rainfall	+15%	-10%	+15%
Temperature	+1.25°C	+1.25°C	+1.25°C

Table 5.4. Land Use Change Scenarios.

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

Table 55 Duarigle catchment – Land Use and Climate Change effects

	Non Modified				**Land Use Chang +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
Jan	106.17	126.22	0.0116	0.0032	106.17	123.22	0.0116	0.003	106.13	126.21	0.0214	0.0046
Feb	52.594	54.372	0.0039	0.0030	52.594	52.478	0.0037	0.0029	52.724	54.53	0.0062	0.0035
Mar	118.25	94.94	0.0204	0.0075	118.25	92.384	0.0301	0.0085	118.6	95.555	0.0159	0.0085
Apr	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
Jun	14.072	9.3904	0.0000	0.0006	14.072	8.016	0.0000	0.0005	14.106	9.2752	0.0000	0.0006
Jul	37.052	12.357	0.0001	0.0009	37.052	10.818	0.0001	0.0007	37.104	12.24	0.0001	0.0008
Aug	50.106	17.252	0.0002	0.0012	50.106	15.1	0.0001	0.0009	50.1	16.979	0.0001	0.0011
Sep	213.45	106.03	0.0901	0.0191	213.45	104.59	0.1010	0.0200	213.73	105.57	0.1317	0.0255
Oct	134.89	128.97	0.0364	0.0142	134.89	126.76	0.0364	0.0141	135.06	127.7	0.0570	0.0187
Nov	167.24	142.34	0.0575	0.0190	167.24	140.47	0.0576	0.0188	167.54	143.23	0.0869	0.0247
Dec	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	**1300.3**	**1047.6**	**0.3079**	**0.1066**	**1300.3**	**1017.3**	**0.3256**	**0.1066**	**1302.3**	**1044.8**	**0.4293**	**0.1314**

6. GIS risk assessment of threats to soils

Here we present GIS results of our (Zhang and Mcgrath, 2004: Zhang et al., 2008, 2011) risk assessment of the threats to soils: *surface sealing; erosion*, *loss of organic matter;* and *landslides*.

6.1 Surface sealing

The 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 seems to be wrong, and may be related to the older techniques of satellite image interpretation. In 2006, the total area of surface sealing in Ireland was 1500.4 km^2. With the total land area of 71222.7 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 Figure 6.1.

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
111	Continuous urban fabric	50.7	28.2	28.3	0.0397%
112	Discontinuous urban fabric	711.8	939.7	1080.1	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	1301.8	1500.4	2.1066%

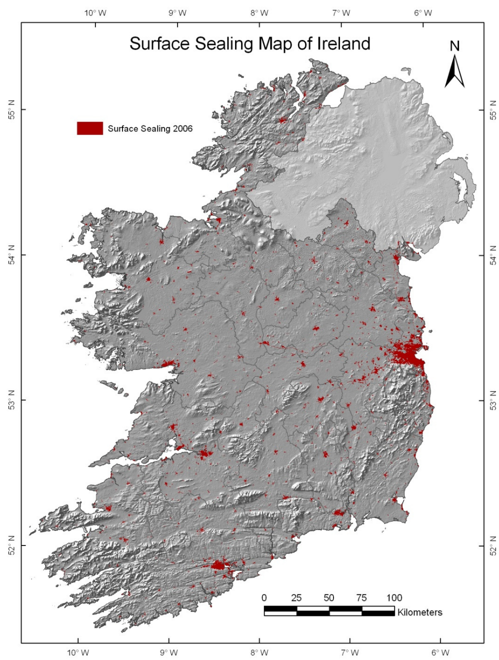

Figure 6.1. Surface sealing map of Ireland in 2006.

The spatial distribution maps demonstrate the urban sprawl in Ireland during 1990-2006, 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 changed due 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 an increase of 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 errors during the production of the GIS data.

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 leafed forest	4	0.2
312	Coniferous forests	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-shub	33	4.5
411	Inland marshes	1	0.1
412	Peat bogs	15	1.7
423	Intertidal flats	1	0.0
Total		1462	206.9

While surface sealing has increased between 1990 and 2006, because of the recession, it is likely that there has been practically no additional surface sealing since 2006. Our numbers in Table 6.1 of an Irish surface sealing extent of 2.1% are higher than that estimated by Eaton et al (2007) and the EC (2008) of ~1.6%. The latter two projects are based on data up to 2000 and (exclude roadways) as we note above we estimate that about 0.3% was added between 2000 and 2006. However if we compare the surface sealing extent in Ireland with our Euro 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 across Europe.

6.2 Update of soil organic carbon 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 1310 samples of SOC data were extracted from the National Soil Database of Ireland (Fay and Zhang, 2007a,b). 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 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 to 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 basin peat.

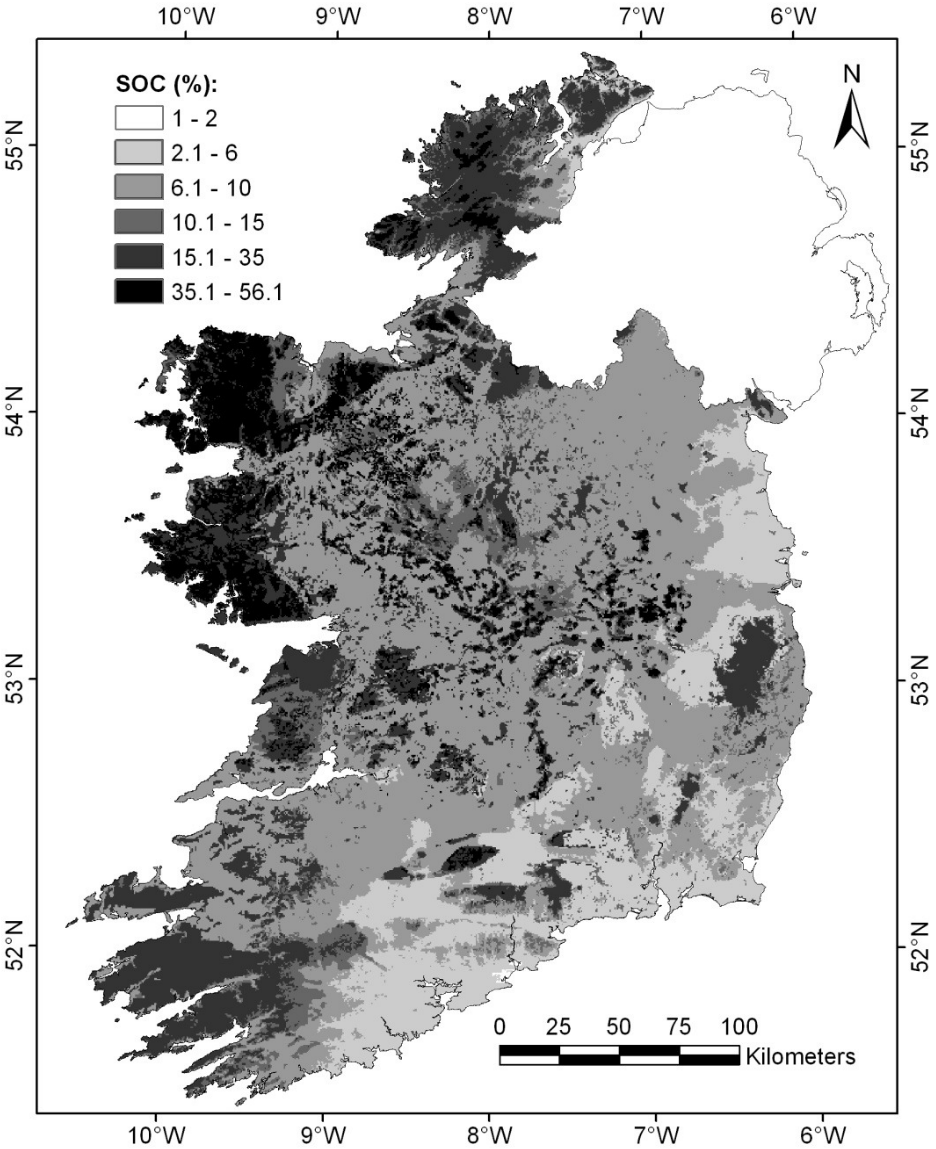

Figure 6.2. Spatial distribution map of SOC in Ireland created using GWR.

6.3 RUSLE and SEDD applications in soil erosion and sediment yield

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

Table 6.3. Sediment yield statistics for pixels for selected catchments (in t/ha/y)

Catchment	Area km^2	Min.	Median	Max.	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

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^{-1} yr^{-1}. However an exception is the catchment Dripsey with sediment delivered of 9.1 t ha^{-1} yr^{-1}. Based on Lewis (2003), the measured sediment delivered for 2002 and 2003 on the 15 km^2 Dripsey catchment was ~ 0.2 t/ha/yr and not 9.1 t/ha/yr as estimated by RUSLE`. However, the use of the default value of 1 for β may not be correct and studies including Ferro and Porto (2000) used β values in the range 0.02 to 0.04. If β of 0.02 were used instead of the default of 1, then the sediment delivered in the Dripsey 15km^2 catchment would be 0.18 t/ha/yr which is what Lewis (2003) measured. The watershed-specific parameter β is singularly accountable for the high values in Dripsey catchment. It needs to be noted that due to lack of actual catchment measurement data for the parameters and lack of actual field experiment work in Ireland, results of soil erosion using RUSLE and SEDD in this study can only be regarded as a first effort.

6.3.2 National scale

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

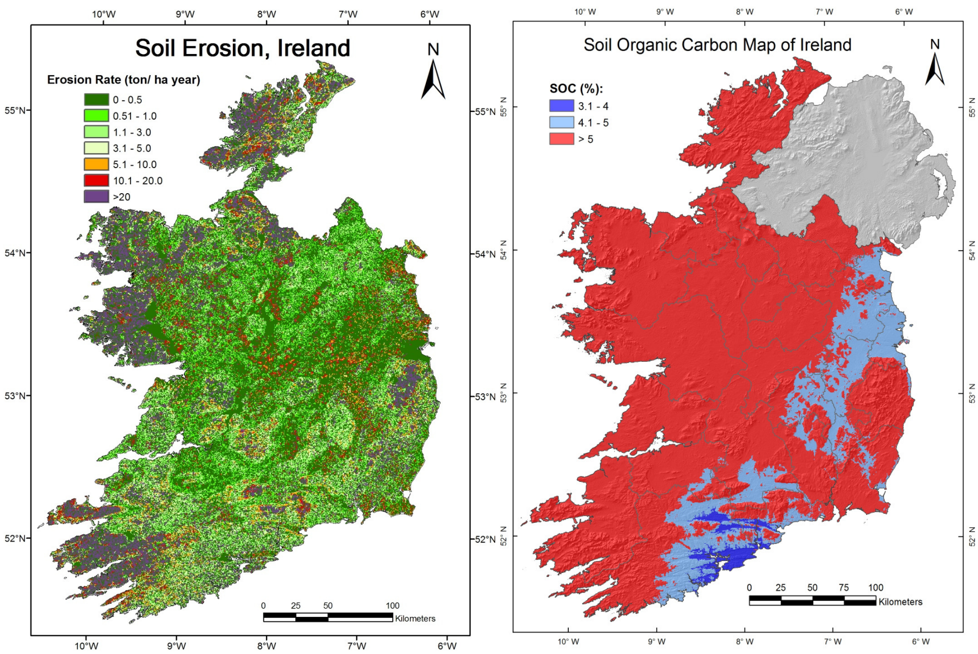

Figure 6.3. (a). Soil erosion risk in Ireland (based on RUSLE model) and **(b).** Spatial distribution map of SOC in Ireland created using GWR. The areas of high erosion risk are those in peatlands at elevated locations. Erosion in peatlands is not dissimilar to landslides in peatlands. Unlike Spain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

Table 5.5 show the statistics for erosion for different land uses. The elevated steep parts of catchments will have high erosion values while flat low lying areas may have no erosion. Results show that the median erosion loss for Ireland is ~0.507 t ha^{-1} yr^{-1}, while for grassland it is 0.454 t ha^{-1} yr^{-1}; for forests it is 0.26 t ha^{-1} yr^{-1}; and for arable it is 11.36 t ha^{-1} yr^{-1}. According to the soil erosion classification by Zachar (1982), Ireland experiences negligible erosion.

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

	~%	min (t/ha/yr)	median (t/ha/yr)	max (t/ha/yr)
Ireland	100.0	0.0	0.5	2912.6
pasture	53.3	0.0	0.5	2483.1
forest	4.2	0.0	0.3	1957.9
arable	7.8	0.0	11.4	316.1

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

(t/ha/yr)	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^{-1} yr^{-1}; for forest was 0.098 t ha^{-1} yr^{-1}; and for arable was 0.22 t ha^{-1} yr^{-1}. It is interesting to note that practically 100% of SSY distribution fell into the 0 to 0.75 t ha^{-1} yr^{-1} band with very few pixels outside this range. The results show that the final sediment yield in Ireland is at a low level and the arable lands suffer more erosion than forests and pasture.

Table 6.6. Summary of RUSLE & SEDD values for Ireland t ha^{-1} yr^{-1}.

	~%	EROSION median (t/ha/yr)	SSY median (t/ha/yr)
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

If we examine Table 6.6, this suggests different sediment delivery ratios (SDR) for different land uses: 0.15 for grassland; 0.37 for forestry; and 0.02 for arable. An earlier review of the literature suggested that 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 it's carbon in fluvial loss is primarily lost as dissolved organic carbon. DOC losses are of the order of 0.1 t ha^{-1} yr^{-1}. 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 matter may far exceed the losses of DOC. In UK work on degraded upland blanket peatlands, POC losses were of the order of 0.5 to 1 t ha^{-1} yr^{-1}.

6.3.3 Climate and land use change scenarios

Risk assessment was also 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 project of Community Climate Change Consortium for Ireland (C4I). The statistical results of soil erosion distribution under different scenarios are displayed in the full SoilH 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/yr). It showed a dramatic change in arable scenarios when forests and pastures are converted to arable lands during the simulation of the model. The nine 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 & forests to arable lands has the most significant impact on soil loss.

6.4 Landslides

Ireland is comparatively benign environment as far as landslides are concerned. This is so, when we compare the extent of landslides across the EU (Italy 48,500; France 10,000) with 136 recorded by the GSI for Ireland. However, events in recent years indicated that potential damages can be caused by landslides. It is therefore important to better understand and map of these hazards. We investigated the relationship between landslides and elevation (Figure 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 the North Western part of Ireland.

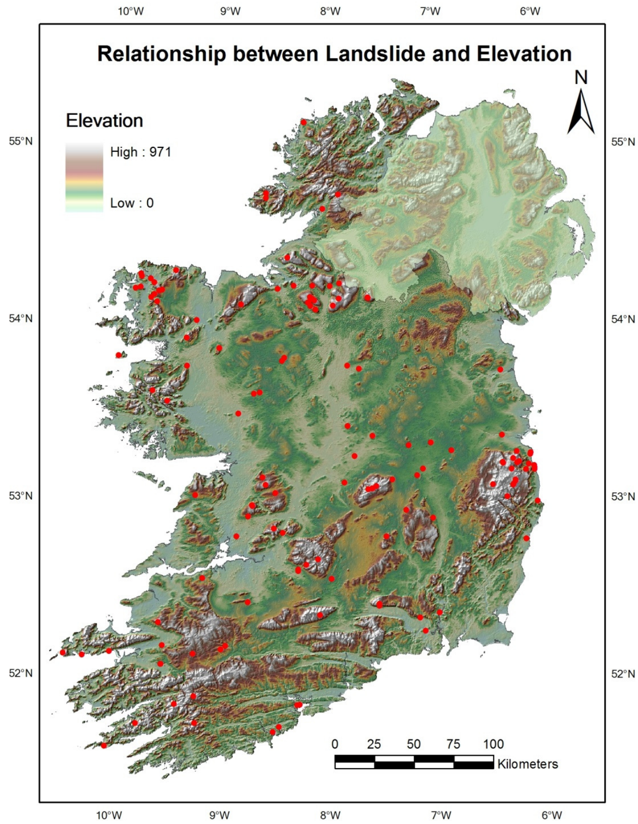

Figure 6.4. Relationship between Landslides and Elevation. Known landslides shown in red dots.

The frequencies for the materials of landslides are summarized in Figure 6.5. The results show that the majority of landlide events (63) had peat as the main material, while some landslides were composed of coarse debris. There were 36 events with materials unspecified.

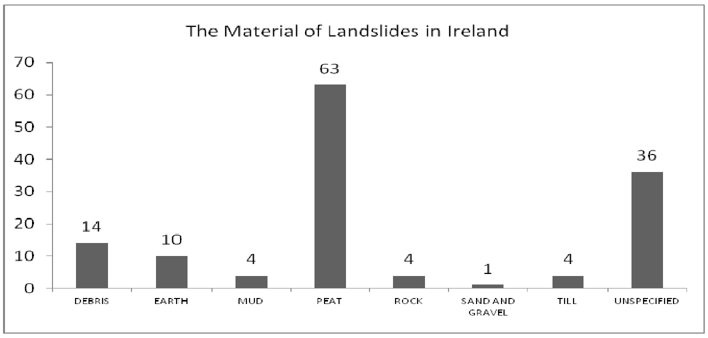

Figure 6.5. Frequencies of materials of landslides in Ireland.

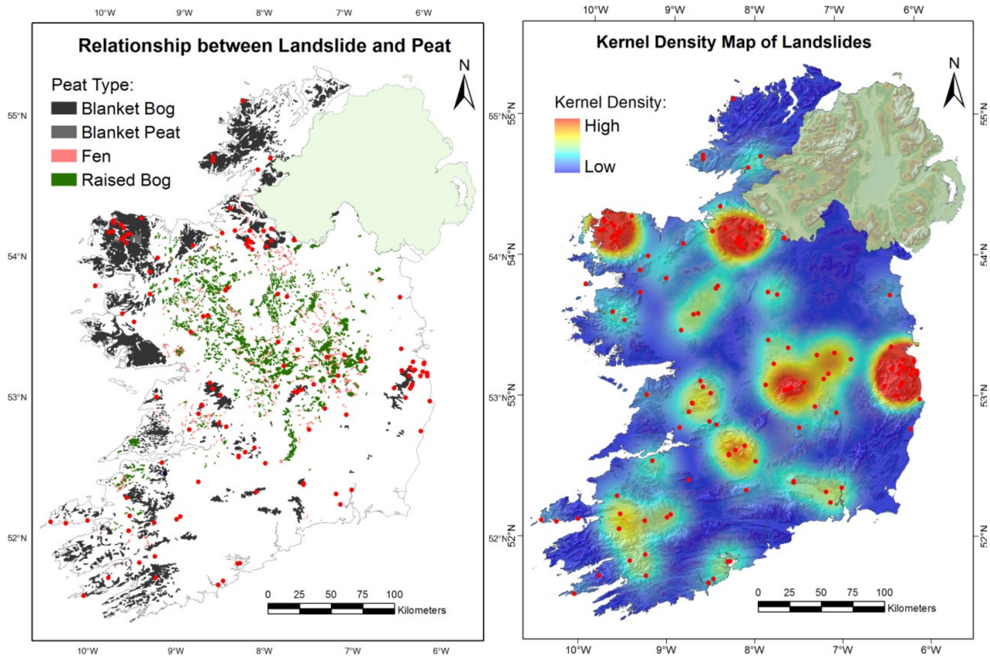

Figure 6.6. (a). Relationship between landslides and peat**.** Known landslides shown in red dots. **(b).** Estimated Kernel Density Map of Landslides in Ireland.

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 Figure 6.6a. The close relationship between landslides and peat is clearly shown in western and south western Ireland, as well as the Wicklow mountain areas. A landslide hazard map was produced using Kernel density method (Figure 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 located in Co. Dublin and Co. Wicklow, North Co. Mayo, and Co. Leitrim, especially in these counties' mountain areas. There was also a good relationship between the high density landslide areas and high elevations.

7. Discussion and Conclusion

Our tasks can be enumerated as follows:

1. determine the soil hydrological properties of a range of Irish soils under different land uses
2. identify a hydrological classification of Irish soils
3. examine the threats to Irish soils from erosion, loss of organic matter, compaction, surface sealing (urbanisation) and landslides.

Here we present a brief discussion on the results and their meaning (under the above three headings) and follow this with a section on conclusions.

7.1 Discussion

7.1.1 Soil hydraulic properties

Knowledge and understanding of soil hydrological properties 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/runoff modelling – to examine the threats to soils such as: erosion, loss of organic matter, compaction, surface sealing (urbanisation) and landslides.

The soil hydrological properties of interest are: hydraulic conductivity and the water retention characteristics. Prior to quantifying the soil hydrological properties (at different depths), we first determine some key physical, moisture and chemical properties of soils including: bulk density; porosity; texture (% sand; % silt; % clay); saturation moisture content; infiltration characteristics (e.g. rate of infiltration at saturation); % soil organic carbon.

We sampled 31 mineral soil sites throughout Ireland (3 depths; 0cm, 15cm and 30cm; and 3 replicates) for all of the above. We also sampled one pristine blanket peatland for a 200m transect (14 locations and depths up to 5m).

We found that most of the mineral soils sampled were loams and fitted into the medium loam classification of the USDA soil textural triangle. We found that the % SOC for the mineral sites ranged from lows of ~2% to highs of <10%. We found that the bulk densities ranged from ~0.9 to 1.4 g/cc but were consistently lower that what was expected from their textural classification. This was due to a number of factors including: high % SOC, frequent soil wetting which enables macroporosity and good soil structure to prevail. We found that the porosity was higher than expected from textural classification and in many cases was closer to 60% than an expected <50%. 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 we found that the bulk density at the edges of the peatland boundary (e.g. near the stream) was 0.11 g/cc or twice that at the bog centre. We found no increase of bulk density with depth even as deep as 5m. Conversely the horizontal saturated hydraulic conductivity was

2 to 3 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) we were unable to use the BEST method of analysis of our infiltration tests and had to rely on a variant of it. However we were able to determine the key hydrological properties of the mineral sites sampled, although it was not possible to produce an hydraulic classification of Irish soils in accordance with the more widespread classifications of Schaap et al. (2000) or Clapp and Horneberger (1978) using simple textural divisions and pedotransfer functions composed of soil properties such as %sand, %silt, %clay and %SOC. Our aim was to identify a reliable classification that would maximize the difference in hydraulic properties among different textural classes but minimize the difference within each class. Our data did not show significant difference between the conventional textural classifications. The Irish Forest Service (IFS) classification (e.g. deep well drained mineral; shallow well drained mineral; etc) seems to be a suitable hydraulic classification for Irish soils. Irish soils are different to soils in other climates, due to the high SOC content, the perennial wet climate and the widespread grassland cover. We therefore produced a quantifiable hydraulic classification similar to that of the Irish Forest Service. The existing IFS classification is qualitative and so cannot be used for hydrological modelling. However our quantification of the IFS classification enables it to be used for modelling purposes. This classification is:

- Deep well drained mineral soils; *Ks* ~ 166 ± 534 cm/day
- Shallow well drained mineral soils; *Ks* ~ 22 cm/day
- Deep poorly drained mineral; *Ks* ~ 7.8 ± 6.8 cm/day
- Poorly drained mineral with peaty topsoil; *Ks* ~ 3.1 cm/day
- Alluviums; *Ks* ~ 14.2 cm/day
- Peats; *Ks* ~ 1030 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/runoff model (GEOtop), we examined the three threats to Irish soils of erosion, loss of organic matter (or SOC) and compaction. While there is very little data from field experiments within Ireland for erosion, loss of SOC and compaction, our simulations provide insight to these three threats to Irish soils. We found that erosion in Ireland is likely to be at the lower end of the international scale at levels < 1 t ha^{-1} yr^{-1} and associated sediment delivery yield (SSY) to rivers of the order of ~0.2 t ha^{-1} yr^{-1}. Erosion produced soil organic carbon (SOC) which ends up in suspended sediment in streams is of the order of 10 kg ha^{-1} yr^{-1}. The SOC loss is in the range 2.5 to 4.5% of the in-stream sediment.

We infer from our field experiments of compaction and the lower than expected bulk densities (from textural analysis), that there is little compaction in the mineral soils we sampled. Our simulations using GEOtop of compaction (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 un-compacted soils. The changed partitioning of precipitation (infiltration vs surface runoff) after compaction causes decreases in infiltration and increases in surface runoff, resulting in greater flood peaks, more erosion and greater SOC loss.

Our simulations of land use change in the Glencar peatland (increase forestry % 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 runoff. Our peatland measurements and modelling show that carbon lost as dissolved organic carbon (DOC) in stream-flow ranges from ~10 kg ha^{-1} yr^{-1} to ~150 kg ha^{-1} yr^{-1}. Low DOC export levels are associated with catchments dominated with mineral soils, while the highest values are associated with stream running through peatland.

We examined the threats to soil quality from surface sealing (urbanisation) and landslides using GIS techniques. We 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 land area while urban plus suburban and road infrastructure cover close to 1.6%. However using data up to 2006, our updated estimate of total surface sealing is ~ 2.1%. This compares to an EU range of 0.15% (Iceland) to 13.7% (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 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 Geological Survey of Ireland recorded 117 landslides by 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 patters 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, we found that 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 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 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

We find no evidence of widespread soil degradation across the Irish sites that we examined in this project. This is in contrast to our EU neighbours who suffer widely the threats that we 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 that we examined and the naturally occurring perennial low intensity rainfall and high levels of soil organic carbon combined with the widespread land cover of grassland seems 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 with it 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. Our nearest neighbours are all at levels twice or more. Of the 136 landslides documented by the Geological Survey Ireland, half are in peatlands and most are recent, and are attributed to climate effects, road construction and wind farm development. However on the international scale (e.g. Italy has recorded more than 500,000), 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) that the threats that were examined in this report. We recommend the EPA to address 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, we recommend that the EPA address field experimental research at the catchment scale. This will also enable more robust modelling efforts using RUSLE, SEDD or process based rainfall/runoff models (e.g. GEOtop).

7.3 Scientific contribution of this project

Theses

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