Rainfall Intensity and Soil Erosion by Water: Limitations of Current Erosion Models and Implications for Erosion Model-based Studies under Future Climates

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ABSTRACT

Existing simulation studies of the effects of future climate change upon erosion indicate that, under land usages that leave the soil unprotected, even minor increases in rainfall amounts are likely to result in disproportionately large increases in erosion, but make the simplifying assumption that distributions of future rainfall intensities remain unchanged from the present. This research aims to determine implications of rainfall-intensity changes on soil erosion using computerised models. Thus, this thesis is a step towards the ultimate goal of predicting future rates of soil erosion caused by future rainfall intensity changes. Three soil erosion models, WEPP, EUROSEM, and RillGrow are employed to investigate impacts of various rainfall intensities on runoff and soil loss rates. Two extreme daily rainfall events in summer and autumn are subjectively selected from the tipping-bucket rainfall data, and runoff and soil losses are simulated using three erosion models. Estimated runoff and soil loss rates with high resolution rainfall data are greater than those with low temporal resolution rainfall data. WSIPs (Within-Storm Intensity Patterns) affect soil erosion amount, although runoff was not much affected. An additional daily rainfall event with WSPs (Within-Storm Pauses) within a storm is also selected to highlight effects of intra-storm pause within a storm on soil erosion. For a given depth of rainfall, events with constant low intensity produced dramatically less erosion: thus it appears that assuming a constant (or averaged) intensity throughout a storm does not provide a good representation of natural rainfall with its continuously varying intensity. Analyses of outputs from WEPP simulations reveal a problem that WEPP modifies original rainfall intensity and, thus, simulates erroneous runoff and erosion rates. Analysis of three observational rainfall datasets (i.e. Monthly 0.5° grid data, daily station data and tipping-bucket gauge data) from the South Downs, UK show increases in frequency of extreme events, and an increasing trend in daily rainfall intensity for the future. Future soil erosion rates are estimated using WEPP and CLIGEN (Climate Generator). 30 year-long weather is generated by CLIGEN. Likely future rainfall frequency and intensity are anticipated by changing the mean maximum 30 minutes peak intensity. No future rainfall amount change is assumed. WEPP simulation results suggest that where mean maximum 30-min peak intensity of the wet months increases soil erosion increases at a greater rate than runoff.

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EXTENDED ABSTRACT

Globally, soil erosion by water is a serious environmental problem. One of many approaches to study this problem is to simulate soil erosion using computer models, which help one to understand complex interactions between various conditions of land use, soil types and climate. Existing simulation studies of the effects of future climate change upon erosion indicate that, under land usages that leave the soil unprotected, even minor increases in rainfall amounts are likely to result in disproportionately large increases in erosion. Such studies, however, invariably make the simplifying assumption that distributions of future rainfall intensities remain unchanged from the present. This is unlikely to be the case. In the latest IPCC (Intergovernmental Panel on Climate Change) report, global average water vapour concentration and precipitation are projected to increase during the 21st century. This implies that there will be an increase in the frequency and magnitude of heavy rainfall. Future climate change will certainly affect rainfall intensities, and thus soil erosion, but our ability to forecast future rainfall intensities is limited by the shortcomings of GCMs (General Circulation Models).

Therefore, the main objective of this research is to investigate possible implications of climate change for future erosion with reference to rainfall intensity changes by analysing the response of erosion models to arbitrary rainfall intensity changes, and implicitly the process understanding on which the models are based. Thus, this research is a step towards the ultimate goal of predicting future rates of soil erosion caused by future rainfall intensity changes.

Three soil erosion models, WEPP, EUROSEM, and RillGrow are employed to investigate impacts of various rainfall intensities on runoff and soil loss rates. Two extreme daily rainfall events in summer and autumn are subjectively selected from the tipping-bucket rainfall data, and runoff and soil losses are simulated using three erosion models. Modelling soil erosion requires highly detailed rainfall-intensity information. Estimated runoff and soil loss rates with high resolution rainfall data are greater than those with low temporal resolution rainfall data. WSIPs (Within-Storm Intensity Patterns) affect soil erosion amount, although runoff was not much affected. An additional daily rainfall event with WSPs (Within-Storm Pauses) within a storm is also selected to highlight effects of intra-storm pause within a storm on soil erosion. For a given depth of rainfall, events with constant low intensity produced dramatically less

erosion: thus it appears that assuming a constant (or averaged) intensity throughout a storm does not provide a good representation of natural rainfall with its continuously varying intensity. Analyses of outputs from WEPP simulations reveal a problem that WEPP modifies original rainfall intensity and, thus, simulates erroneous runoff and erosion rates.

Monthly 0.5° grid data for 100 years are analysed to draw outlines of rainfall trends in the study area. Trends of daily rainfall amount, number of raindays, simple daily intensity index, number of raindays with rainfall amount ≥10 mm, and number of raindays with rainfall amount ≥20 mm are also investigated with 9–93 years long daily station data. Detailed rainfall-intensity patterns in the study area are examined using tipping-bucket rainfall gauge data. Analysis of three observational rainfall datasets show increases in frequency of extreme events, and an increasing trend in daily rainfall intensity for the future. Long-term monthly 0.5° grid data analysis shows a statistically significant decreasing trend in July rainfall amount over the 1901–2000 period. With daily observational data, March rainfall amounts in the last two decades and July rainfall amounts in the last decade show a downward trend although these are not significant. Simultaneously, the numbers of raindays per month show downward trends. Annual daily rainfall-intensity over 1904–1996 has increased significantly. This is mainly the result of an increased number of extreme rainfall events (≥10 mm) compared to an annual number of raindays.

Future soil erosion rates are estimated using WEPP and CLIGEN (Climate Generator). 30 year-long weather is generated by CLIGEN. Likely future rainfall frequency and intensity are anticipated by changing the mean maximum 30 minutes peak intensity. No future rainfall amount change is assumed. WEPP simulation results suggest that where mean maximum 30-min peak intensity of the wet months increases soil erosion increases at a greater rate than runoff.

Several further investigations are suggested on: measurement of runoff and soil loss with discontinuous storms and their implications for soil erosion; an investigation of relationships between duration of no-rain period and soil erosion; development of an erosion model that can fulfil the requirements suggested in this thesis; an investigation of the relationship of intra-storm intensity patterns and data scale (temporal and spatial); an investigation of the trend of intra-storm intensity and no-rain periods.

ACKNOWLEDGEMENTS

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Introduction

Chapter 1

THE PROBLEM IN CONTEXT

1.1 Introduction

Soil is an important resource for the survival of the human race and is a central component of environmental systems, together with water, air and radiation from the sun. Undoubtedly, soil is one of the essentials for life on Earth. Scientists have investigated various soil properties to ensure good yields of crops, fibre and fuel (Cresser *et al.*, 1993). However, soils do not necessarily always provide ideal conditions for plant growth. Many soil processes can constrain plant growth: soil hydrology is fundamental for most of these (Hudson, 1971; Evans, 1980; Kirkby, 1980; Morgan, 1995). Among the most serious is soil erosion by water.

Globally, soil erosion by water is a serious present-day environmental problem and its consequence is subject to extensive investigations (Kirkby, 1980; Morgan, 1995). Previously published simulation studies of the effects of future climate change upon erosion indicate that, under land usages that leave the soil unprotected, even minor increases in rainfall amounts are likely to result in disproportionately large increases in erosion (Kirkby, 1980; Favis-Mortlock and Boardman, 1995).

Soil erosion rates may be expected to change in response to changes in climate for a variety of reasons, the most direct of which is the change in the erosive power of rainfall (Favis-Mortlock and Savabi, 1996; Williams *et al.*, 1996; Favis-Mortlock and Guerra, 1999; Nearing, 2001; Pruski and Nearing, 2002*a*). Existing studies however almost invariably make the simplifying assumption that distributions of future rainfall intensities remain unchanged from the present (Favis-Mortlock, 1995; Favis-Mortlock and Boardman, 1995). This is unlikely to be the case. Intensities may change and/or the frequency of occurrence of high-intensity events may change (Houghton *et al.*, 1996; Watson *et al.*, 1998). Any increases in the occurrence of high-intensity rainfall—even without any associated increases in rainfall amounts—may well increase runoff, and hence erosion rates (Kirkby, 1980; Morgan, 1995; Parsons and Gadian, 2000). Thus, future climate change will certainly affect rainfall intensities but our ability to forecast future intensities is limited by the shortcomings of General Circulation Models (GCMs) (Favis-Mortlock and Boardman, 1995).

Very few studies have attempted to quantify impacts of changes in future rainfall intensity (IPCC Working Group II, 2001). Results from these few studies suggest that more (or similar) rainfall than at present will occur on fewer raindays—implying an increase in the frequency of heavy rainfall amounts (Watson *et al.*, 1998). If these predictions are correct, the implication for future erosion rates are clear.

For these reasons, there is a urgent need for greater understanding of future rainfall intensity changes in order to improve the ability of soil erosion prediction.

1.2 Soil Erosion Processes

1.2.1 Introduction

> "Erosion by water is the redistribution and removal of the upper layers of the soil, both by the action of falling rain, and by water flowing over the soil during and after rain or following snowmelt." (Favis-Mortlock, 2002)

The erosion of soil by water and wind is a naturally occurring process, which is commonly accelerated by human activity. However, when soil erosion occurs at a greater rate than the rate of soil formation, soil erosion is considered as an environmental problem. Soil erosion is a ubiquitous problem that threatens an important and non-renewable resource such as the agricultural land that is suitable for cultivation (on-site impact) (Boardman, 2003). In addition to removing a valuable resource, soil erosion leads to increased sediment input to nearby watercourses, resulting in, for example, the silting-up of dams and contamination of drinking water (off-site impact) (Mejia-Navarro *et al.*, 1994; Kitchen *et al.*, 1998).

Soil erosion problems can be viewed in three different ways (Kirkby and Morgan, 1980). Firstly, in the broadest view, soil erosion can be compared with other processes of landscape denudation. When and where it is the most rapid process, soil erosion should be recognised as the dominant problem. This view leads to the question of what erosion rates can be tolerated in the long-term. Secondly, a narrower overview examines soil erosion with its immediate climatic and vegetational controls. This then leads to the question as to how well the processes involved in raindrop impact, flow generation, and sediment resistance are understood. Thirdly, soil erosion can be considered in relation to its broad patterns in time and space. Yet, the reasons for the temporal and spatial

distributions of soil erosion are only partially understood (Quine and Zhang, 2002; Gómez *et al.*, 2005; Wakiyama *et al.*, 2010).

Soil erosion by water is most active where rainfall cannot infiltrate the soil, but flows over the surface. The flow travels relatively fast, and is able to carry soil materials away mainly by shear stress, although other sub-processes also contribute (Kinnell, 2000). In some cases, only an hour or two of contact time with the surface soil is needed to carry away an appreciable amount of material. Thus, where overland flow is dominant, soil erosion by water is likely to be the main process of landscape denudation. When a large depth of water flows rapidly over the surface with correspondingly large hydraulic forces, soil erosion acts catastrophically. These conditions are most commonly found in semi-arid areas, but fields cleared for agricultural purposes are also subjected to erosion in almost any climate, which can on occasion be severe.

Semi-arid areas are very sensitive to small natural changes in climate and in such areas it is difficult to separate natural from man-induced changes in erosion rates. However, even in temperate-humid areas increased erosion resulting from farming can be sensitively dependent on the extent of the change in vegetation cover, the total rainfall at periods of low cover, and the intensity of the rains.

Therefore, two distinct types of area appear to be at great risk of soil erosion. The first are semi-arid areas, and the second are locations in temperate areas that have been stripped of vegetation for crop cultivation. A soil erosion rate can reach at its maximum where intense rainfall occurs during the period of lowest vegetation cover. This is normally the case in semi-arid climates or in temperate areas which have been left bare at the time of the heaviest annual rainfall. In such cases, when the rainfall increases, soil loss increases, so that the erosional peak tends to be synchronised with the rainfall peak and this relationship becomes clearer when the soil becomes more unprotected.

When soil erosion problem is to considered, it also is worthwhile to take long-term effects of soil erosion into consideration. For example, when soil erosion occurs at a rate of one millimetre per year, it might not have apparent effect in a human lifetime. However, over a longer-term, the effect can be considerable. To put this into perspective, topsoil of 15 cm thickness in general would be completely removed after 150 years if erosion rates stay as high as 1 mm/year in average with no additional soil formation in the area. Topsoil contains a high proportion of soil organic matter and the finer mineral fractions, which provide water and nutrient supplies for plant growth. This may look as an oversimplification of the erosion process and soil formation, but it gives us an idea of the long-term effect of soil erosion.

1.2.2 Rainfall

1.2.2.1 Raindrop Splash

The process of erosion by water is a two-phase process: detachment and transport (Morgan, 1995). Individual soil particles are detached from the soil mass by the impact of raindrops. The erosive power of raindrops weakens and loosens the soil surface, and flowing water transports the soil particles (Kinnell, 2000). When sufficient transporting energy is no longer available, a third phase, deposition, can occur.

Raindrop splash distributes soil particles radially away from the site of detachment. The raindrop detachment-splash transport (RD-ST in Figure 1.1) process is effective where rainfall intensities are high, for example, as a result of convective rainstorms. However, splash transport (ST) is a generally inefficient transport mechanism. If the soil has virtually no slope, soil particles splashed away from the point of impact are replaced by soil particles detached by other raindrops in the surrounding area (Kinnell, 2000; Zartl *et al.*, 2001). Even if the soil surface has a slope, net downslope transport by

raindrop splash alone is generally small (Kinnell, 2001).

When water flows start to build up, the soil surface becomes protected from direct raindrop impact, and another transport mechanism begins to active. Raindrops with sufficient kinetic energy to penetrate through the flow may detach and lift soil particles into the flow, which then carries them downstream until it looses sufficient transporting energy to carry the particles. Soil particles transported by the flow then fall back to the soil surface of lower grounds. This transport process is termed Raindrop-Induced Flow Transport (RIFT in Figure 1.1) (Kinnell, 1990). While RIFT is more efficient than ST, it still requires numerous raindrop impacts to move soil particles downstream.

As rain continues, thin surface water flows become capable of moving loose soil material on the top of the surface, but might not be capable of detaching soil material from the soil mass. In many cases, soil particles are detached by the help of raindrop impacts, and carried away downstream without the need for raindrops to be involved in the transport process. This raindrop detachment-flow transport (RD-FT) process is more efficient than RD-RIFT. In a typical field, both RD-RIFT and RD-FT occur simultaneously in the same flows.

When the critical stream power ($\Omega_{c(\text{bound})}$) for flow to detach soil particles from soil mass exceeds stream power (Ω), flow detachment (FD) occurs (Kinnell, 2000). Once soil materials are detached and transported by flow (FD-FT), erosional channels are generated (Figure 1.1). As these channels develop and increase in size to become large rills and possibly even gullies, processes such as gravitational collapse of channel walls and heads become important (Boardman *et al.*, 2003).

1.2.2.2 Rainfall Intensity

The erosive power of rainfall has long been appreciated by studies on soil erosion (Musgrave, 1947; Wischmeier and Smith, 1958). Nevertheless, obtaining information

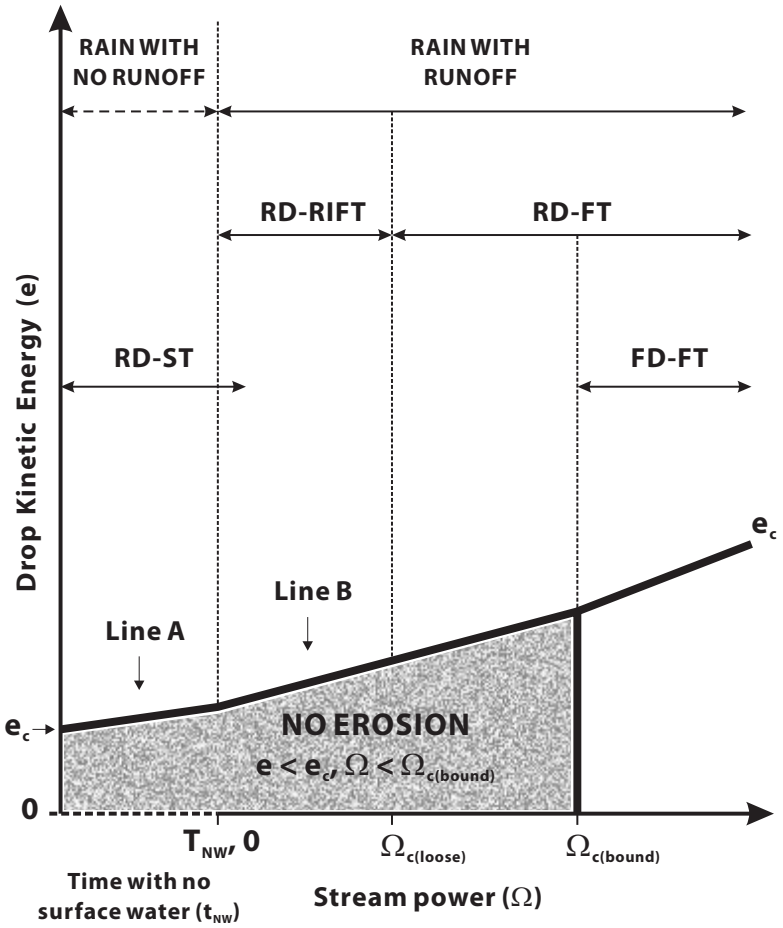


Figure 1.1 Detachment and transport processes associated with variations in raindrop and flow energies. T_{NW}: total time when rain falls and there is no surface water. e_c: critical raindrop energy to cause detachment; raindrop-induced erosion occurs when drop energy is equal or greater than e_c. Line A: e_c when raindrops are detaching soil particles from the soil surface prior to flow developing. The slope on this line is used to indicate increasing resistance to detachment caused by, for example, crust development. Line B: e_c when raindrops are detaching soil particles from the soil surface when flow has developed. The slope on this line is used to indicate increasing utilization of raindrop energy in penetrating the flow when flow depth increases as flow power increases. $\Omega_{c(\text{loose})}$: critical stream power required to transport loose (pre-detached) soil particles. $\Omega_{c(\text{bound})}$: critical stream power required to detach particles bound within the soil surface (held by cohesion and interparticle friction). RD-ST: raindrop detachment and splash transport. RD-RIFT: raindrop detachment and raindrop-induced flow transport. RD-FT: raindrop detachment and flow transport. FD-FT: flow detachment and flow transport(From Kinnell, 2005*a*).

on rainfall intensity for soil erosion is very much problematic. One way of measuring rainfall intensity would be measuring size, distribution and velocity of raindrops, so that the kinetic energy of the rainfall can be calculated (Cerda, 1997; Lascelles *et al.*, 2000). This can be seen as a 'bottom-up' approach. Another method would be simply to measure rainfall amount and duration, so that intensity can be obtained by dividing rainfall amount by duration (i.e. rainfall amount per unit time) (Osborn and Hulme, 1998). This is a 'top-down' approach. However, both approaches have their own shortcomings (Parsons and Gadian, 2000; Schuur *et al.*, 2001; Garcia-Bartual and Schneider, 2001).

Although rainfall intensity plays a very important role for soil erosion, it is important to recognise that the vital variable for soil erosion is not rainfall intensity itself, but rainfall energy. This rainfall energy varies in association with rainfall intensity. As raindrops increase in size, their terminal velocity increases. This increases the kinetic energy of raindrops. The total kinetic energy of rainfall also increases with increasing number of raindrops during a given time. The total kinetic energy of rainfall may be estimated from the distribution of raindrop size and number of raindrops during a storm. The accuracy of this estimation is, however, limited by natural variations in rainfall characteristics (van Dijk *et al.*, 2002). Yet, in natural rainfall events, the relationship between rainfall intensity and energy is neither so clear, nor simple. Despite this, simple assumptions about the rainfall intensity-energy relationship are often made in studies on soil erosion, in particular, simulation studies, as rainfall intensity is the only easily modifiable control on rainfall energy in such studies.

Parsons and Stone (2006) ran a laboratory-based rainfall simulation experiment to determine the implications of temporal variation of rainfall intensity for rates of soil loss. He found that erosion is least for the constant-intensity storms. This is highly significant because soil-erosion models are typically calibrated using data obtained from

constant-intensity experiments. Moreover, storm pattern does not appear to affect the volume of runoff, but it does affect the quantity of eroded sediment. In particular, the constant-intensity storm patterns are associated with low erosion rates. Storm pattern also affects the size-distribution of the eroded sediment. Parsons and Stone (2006) therefore concludes that the relationship between rainfall energy and interrill erosion is more complex than is currently assumed in process-based models of soil erosion.

Other studies also note that there are complex interactions between raindrop size, velocity and the duration of rain, which control the erosive power of rainfall (Kinnell, 1981; Brandt, 1990; Salles *et al.*, 1999; van Dijk *et al.*, 2002).

1.2.3 Soil Type

Soil erodibility is an estimate of the resistance of the soil to erosion, based on the physical characteristics of each soil (Morgan, 1995). Although erodibility varies with soil texture, aggregate stability, shear strength, infiltration capacity and organic and chemical contents, soils with high infiltration rates, higher levels of organic matter and improved soil structure have a greater resistance to erosion, in general (Morgan, 1995).

Erodible soils have restricted clay content (Bryan, 2000). Soils with more than 30–35% clay are generally coherent and form stable soil aggregates, which are resistant to raindrop impact and splash erosion (Evans, 1980). Clays often have rough surfaces to store much water, and are resistant to sheet and rill erosion. Sands and coarse loamy sands, on the other hand, have high infiltration rates and resistant to erosion, and even if this is exceeded, sands (more than 0.3 mm diameter) are not easily eroded by flowing water or by raindrop impact (Evans, 1980; Marshall *et al.*, 1996).

Sandy soils are however more erodible than clayey soils because the aggregates of these sandy soils slake more readily and seal the soil surface (LeBissonnais, 1996). Loamy

soils are also particularly at risk of sealing (Ramos *et al.*, 2000).

After cultivation, the soil surface becomes rough. The amount of water, which can be stored on the surface before runoff takes place, is thus large at this time. Surface roughness is least after drilling and rolling of the seedbed, and differences between soil types are smallest (Robinson and Naghizadeh, 1992). For similar soil types, the timing of cultivation can affect the storage volume, for example, a clay surface prepared in winter can have more than twice as much storage volume as a surface prepared in spring (Evans, 1980).

Moreover, stony soils are generally less vulnerable to erosion as the surface stones not only protect the soil, but also increase infiltration by providing larger pores between stones (Agassi and Levy, 1991; Poesen and Lavee, 1994; de Figueiredo and Poesen, 1998). However, when rock fragments are well-embedded in a surface seal, a positive relation for runoff and sediment yield is found (Poesen and Ingelmo-Sanchez, 1992). A negative relation occurs either where rock fragments are partly embedded in a top layer with structural porosity or where the rock fragments rest on the surface of a soil having either textural or structural pore spaces (Poesen and Ingelmo-Sanchez, 1992).

1.2.4 Topography

There are two aspects of topography that affect erosion: slope angle and length. Normally, erosion would be expected to increase as the slope steepness increases (Liu *et al.*, 1994). Soil erosion by water also increases as the slope length increases because of increases in velocity and volume of runoff (Liu *et al.*, 2000). Water depth increases with downslope distance so that interrill soil erosion is affected by slope length (Gilley *et al.*, 1985*b*). Water depth then affects soil detachment and overland flow sediment transport capacity (Gilley *et al.*, 1985*a*). Slope angle is also closely related to the effectiveness of splash erosion (Kinnell, 2000; van Dijk *et al.*, 2003).

The location of downslope is an important factor that determines the development of rills on a hillslope. However, there is another factor that is closely related to the dynamics of initiation and growth of rills. The minute variations of soil surface topography, also known as microtopography, can play an important roll on this "rill competition".

Microtopography is not temporally static because erosional processes will continuously modify the surface of soil during a rainfall event. As a result, runoff during the latter part of the event will flow over a soil surface that has been modified and different from the surface earlier in the rainfall. Thus, erosive modification of microtopography constitutes a feedback loop which might be expected to operate in a positive sense. The most 'successful' rills (i.e. those conveying the most runoff) will modify the local microtopography to the greatest extent, and so will most effectively increase their chances of capturing and conveying subsequent runoff.

Favis-Mortlock *et al.* (2000) previously recognised the importance of microtopography in the initiation and the development of rills, and developed a erosion model, RillGrow, using a self-organising dynamic systems approach. More about RillGrow is included in Section 1.5.5.

1.2.5 Land Use

Soil erosion potential is highest where the soil has no or very little vegetative cover. Vegetation cover protects the soil from direct raindrop impact and splash, and tends to slow down surface runoff. On a field with complete vegetation cover, runoff and erosion are comparatively small, often less than 5% of runoff and 1% of erosion from bare soil, respectively (Braskerud, 2001; Rey, 2003). One reason is because the infiltration rates of the vegetated field are relatively higher than those on bare soils as the field often has a better soil structure and more stable aggregates (Robinson and Phillips, 2001). When runoff does take place, the leaves and roots of plants inhibit the flow by reducing the

velocity of the flow (Braskerud, 2001; Rey, 2003). On soils with less than 70% vegetation cover, runoff and erosion increase rapidly when rainfall occurs (Favis-Mortlock and Savabi, 1996). Under less than 20–30% vegetation cover, runoff and erosion are related to the amount of bare ground, increasing as the proportion of bare ground increases (Favis-Mortlock and Savabi, 1996).

The effectiveness of any crop management system against soil erosion by water also depends on how much protection is available at various periods during the year, relative to the rainfall amount that falls during these periods. In this respect, crops which cover for a major portion of the year (e.g., alfalfa or winter cover crops) can reduce erosion much more than can crops (e.g., row crops) which leave the soil bare for a longer period of time and particularly during periods of intense rainfall (Zhang *et al.*, 1995*a*,*b*).

1.3 Soil Erosion and Rainfall Intensity

Some arbitrarily-chosen, but notable, high-intensity rainfall events and resulting severe soil erosion events which are described in the literature are summarised below.

South Downs, East Sussex, UK, October 1987 (Boardman, 1988) Heavy rainfall on 7 October 1987 and subsequent storms resulted in soil losses over 50 m^3/ha on several fields and over 200 m^3/ha on one field in the eastern South Downs (Boardman, 1988). Monthly rainfall totals at Southover, Lewes, were 54.3 mm for September and 270.9 mm for October 1987. Rainfall recorded at Southover, Lewes, on 7 October 1987 was 50.2 mm with a maximum short period intensity of 6.7 mm/h for 5.5 hours including 40 mm/h for 15 minutes.

Substantial rills or gullies were formed by the rainfall event on 7 October 1987. As a result of this, following rainfalls as low as 7 mm caused runoff and erosion (Boardman, 1988). Although there are no event-by-event records available for soil losses, it is evident

that the rainfall on 7 October 1987 played an important role, by contributing to rill or gully generation, on soil erosion in the area. However, the main factors responsible for the severe erosion were land use and farming practices.

South Downs, East Sussex, UK, October 2000 (Boardman, 2001) Exceptional rainfall in October and November 2000, especially a 24-hour fall of about 100 mm, led to extensive erosion and property damage (Boardman, 2001). The rainfall was typical of frontal, low-intensity events that usually occur in British winters but it lasted for a longer period than usual period. In a 24-hour period prior to 09:00 on 12 October (i.e. 11 October rainday), a total rainfall of 89.9 mm was recorded (Boardman, 2001). In a 10-hour period of continuous rainfall (23:00–09:00) 63.8 mm fell with a maximum intensity of 11.4 mm/h and a maximum short-period intensity of 3.6 mm/min (i.e. 216 mm/hr) (Boardman, 2001).

Rainfall of 100 mm in 24 hours has a return period of well over 100 years and a intensity of 11 mm/h is to be expected every year (Boardman, 2001). This means that the rainfall on 11 October 2000 has a rainfall intensity that is commonly observed in the area, but the total amount and duration are very unlikely in the area. It is noted that high intensity rainfall within prolonged low intensity rainfall at the time of year when the agricultural land is most vulnerable may result in extensive erosion events.

Vicrello, Tuscany, Italy, May 1994 (Torri *et al.*, 1999) A rainfall depth of 77.8 mm fell on a field plot with a bare soil in Vicrello, Tuscany, Italy (Torri *et al.*, 1999). The storm lasted for over 28 hours and caused a soil loss of 126.2 t/ha. Maximum intensity averaged over 10 minute was 120 mm/h.

Northern Ethiopia Highlands, 1998-2000 (Nyssen *et al.*, 2005) Rainfall intensity in Northern Ethiopia Highlands was monitored using a tipping bucket rain gauge during 1998-2000 (Nyssen *et al.*, 2005). Overall rain intensity in the area is low. 88% of total rain

volume falls with an intensity <30 mm/h. Most storms have a low intensity with a brief high intensity part. This high intensity can be observed at the beginning, in the middle or at the end of the storm. Although area-averaged intensity was low in this area, it was found that maximum rain intensity at individual locations exceeded by far the threshold values for excessive rain (see Table 5, Nyssen *et al.*, 2005). Rainfall intensities beyond these thresholds were known to cause >50% of total soil losses (Krauer, 1988). Large rain erosivity in the area is due to larger median volume drop diameters (D_{50}) than those reported for other regions of the world, rather than due to high intensity.

Hadspen, Somerset, UK, May 1998 (Clark, 2000) Total rainfall amount of 47.6 mm fell in Hadspen, Somerset, UK on 13 May 1998 (Clark, 2000). Most of rain fell between 2115 GMT to 2130 GMT reaching rainfall intensity of >100 mm/h. In Nettlecombe Hill and Higher Hadspen, ploughed fields on slopes with 2–11° eroded at the rates of 1.412 tonnes/m^3 and 1.312 tonnes/m^3, respectively. Total soil loss from two area was 72.1 tonnes.

Ashow, Warwickshire, UK, August 1999 (Harrison and Foster, 1999) On 20 August 1996 in Ashow, Warwickshire, the storm commenced at 1930 BST. Rainfall intensity was low until 2030 BST when 24.5 mm of rain fell in 30 min and a total of 33.5 mm fell before midnight.

One of two fields in the catchment was planted with oilseed rape eight days before the storm. The field was ploughed and power-harrowed, and then seed drilled with a low ground pressure buggy. It was subsequently rolled by a tractor with low ground pressure tyres. The other field was harvested of wheat and barley, and then rough ploughed, the soil clods being broken up using rotating discs.

Extensive erosion of top soil occurred, followed by the development of gullies and rills by overland flow during the storm. Approximately 790 t of sediment was eroded

from the two fields excluding the sediment that reached nearby river (River Avon, UK). Average sediment yields was 49.7 t/ha which is equivalent to the average ground lowering of 3.8 mm.

1.4 Rainfall Intensity and Climate Change

Many studies using GCMs predict an increase in global average precipitation in response to global warming induced by greenhouse gases (Houghton *et al.*, 1996; IPCC Working Group II, 2001; IPCC Working Group I, 2001; Jones and Reid, 2001). This increase in global average precipitation has been based on the assumption that an increasing global-mean temperature will intensify the hydrological cycle (Houghton *et al.*, 1996). The IPCC reported that there has been a very likely increase in precipitation during the 20th century in the mid-to-high latitudes of the Northern Hemisphere (IPCC Working Group I, 2001). Climate models are also predicting a continued increase in intense precipitation events during the 21st century (IPCC Working Group II, 2001).

In addition, there has been a number of investigations using observed data that provided some evidences for a significant increase in extreme precipitation (Karl *et al.*, 1995; Karl and Knight, 1998; Osborn *et al.*, 2000; Osborn and Hulme, 2002). Karl *et al.* (1995) and Karl and Knight (1998) observed increases in extreme precipitation (greater than 50 mm per day) in the United States using historical data over the period 1910–1996. Osborn *et al.* (2000) and Osborn and Hulme (2002) also observed an increasing trend in intense daily precipitation over the period 1961–2000 in the United Kingdom. They found that, on average, precipitations were becoming more intense in winter and less intense in summer.

The findings by Osborn *et al.* (2000) and Osborn and Hulme (2002) are generally consistent with the results from the GCM simulations (Jones *et al.*, 1997; Jones and

Reid, 2001). However, IPCC Working Group II (2001); IPCC Working Group I (2001) indicated that potential changes in intense rainfall frequency are difficult to infer from global climate models, largely because of coarse spatial resolution. The ability of GCM integrations and operational analyses to simulate realistic precipitation patterns, spatially and seasonally, is also generally not as good as the ability to predict temperature (McGuffie *et al.*, 1999). The likelihood of finding real trends in the frequency of extreme events becomes lower the more extreme the event (Frei and Schär, 2001). The same authors demonstrate this by applying known trends in the scale parameter to synthetic data series, and then attempt to identify statistically significant trends in the frequency of various extreme events.

There are various physical reasons (see Trenberth, 2000) why a large increase in the magnitude of heavy precipitation may occur with only a correspondingly small increase in mean precipitation. It is even possible that heavy precipitation occurrence could increase when mean precipitation decreases, if there is a more radical change in the precipitation distribution (Osborn and Hulme, 2002).

A recent study by Nearing (2001) estimated potential changes in rainfall erosivity in the United States during the 21st century under climate change scenarios. He concluded that, across the United States over an 80 year period, the magnitude of average changes in rainfall erosivity was 16–58%. This variability in the magnitude was due to the method (two GCM models and two scenarios) that he used to predict the changes in rainfall erosivity. Regardless of which method was used, he suggested that changes in erosivity will be critical at certain locations.

In order to run a soil erosion model such as WEPP (Water Erosion Prediction Project, See Section 1.5.3 for more details), for example, various weather parameters for each day of the simulation period are required (Flanagan and Nearing, 1995). These weather variables (e.g. rainfall depth and duration, peak storm intensity and time to

peak, minimum and maximum temperatures, dew point temperature, solar radiation, wind speed and direction) can either be generated by CLIGEN (CLImate GENerator, See Section 1.5.3.1 for more details) or compiled manually from observed climate data.

Generating climate data for studies on future soil erosion is not a simple task, even with today's climate data, as a starting point, since all erosion predictions must involve modelling extreme weather events. Extreme weather events are rare and occur on the synoptic and even smaller temporal and spatial scales (e.g., heavy showers, gusts and tornadoes) (Schubert and Henderson-Sellers, 1997; Katz, 1999; Coppus and Imeson, 2002). Long integrations of very high-resolution models are required to simulate those extreme events and even then, there is little prospect that sub-synoptic scale events can be successfully resolved in GCMs. GCM grid sizes are too large to properly capture convective elements in the atmosphere, so that precipitation within a short period (e.g., one day) is poorly reproduced by GCMs (Schubert and Henderson-Sellers, 1997).

There are a few ways for resolving this scale issues with GCM data. One way is by using climate data generated directly by Regional Climate Models (RCMs) that are capable of generating climate data with a sub-daily resolution (i.e. 20-min). Another can be achieved by downscaling. There are several approaches for downscaling GCM data into regional scale. Wilby and Wigley (1997) divided downscaling into four categories: regression methods, weather pattern (circulation)-based approaches, stochastic weather generators and limited-area climate models. Among these approaches, circulation-based downscaling methods perform well in simulating present observed and model-generated daily precipitation characteristics, but regression methods are preferred because of its ease of implementation and low computation requirements. RCM data and downscaled data allow predictions to be made at a finer scale than GCMs. All of these methods are widely accepted methods that were often chosen to generate climate data with a sub-daily resolution.

Lastly, IPCC Working Group II (2001) reported generalised results from the analysis of five regional climate change simulations. Although scenarios for precipitation produced by these experiments varied widely among models and from region to region, the results provide very important working envelopes for this research. The results related to precipitation are summarised as follows:

1. Regional precipitation error spanned a wide range, with values as extreme as approximately −90% or +200%.

2. Simulated precipitation sensitivity to doubled CO_2 was mostly in the range of −20% to +20% of the control value.

3. Overall, the precipitation errors were greater than the simulated changes. It can be expected that, due to relatively high temporal and spatial variability in precipitation, temperature changes are more likely to be statistically significant than precipitation changes.

1.5 Soil Erosion Prediction Models

1.5.1 Introduction

To assess the risk of soil erosion, estimates of soil loss rates may be compared with what is considered to be acceptable for conservation purposes; the effects of different conservation strategies may then be determined. Consequently, a technique is required to compare possible soil losses under a wide range of conditions. One way of doing this is using computerised models for soil erosion, which are (like all models) simplified representations of reality. Types of erosion models are categorised by their structures in Table 1.1. It needs to be noted that the categories in Table 1.1 tend to be mixed, nowadays.

Another categorisation scheme is based on objectives and levels of performance. In this scheme, there are two basic types of models in addition to the categories in Table 1.1. One is a screening model, which is relatively simple and designed to identify problem areas. This type of model only requires predictions of the right order of magnitude. The other type is an assessment model, which requires better, more robust, and accurate predictions because it is mainly designed for evaluating the severity of erosion, for example, under different soil management systems. Thus, depending on the purpose to which a model is put, the appropriate level of complexity/simplicity of the model should be established. A clear statement of the purpose of the study is essential; this will serve as a starting point for all modelling procedures.

Our current understanding of erosion processes is greatest over short time periods, seconds to minutes. It is thus problematic when applying this understanding to longer periods, e.g. months to years or even longer, as is necessary for real-world conservation tasks. It may just be feasible for slightly longer periods such as hours or days, but continuous extrapolation is not appropriate (Kirkby *et al.*, 1992; Morgan, 1995). Therefore, longer-term prediction can only be achieved by summing the predictions for individual events, or developing models empirically, using data collected on a long-term basis, or improving our understanding of processes to be able to build physically-based models.

In addition to these temporal extrapolation issues, the spatial extrapolation issues must also be considered. For instance, the detailed requirements for modelling erosion over a large drainage basin (Hooke, 2000) may differ from those demanded by models of soil loss from a short length of hillslope (Goff *et al.*, 1993), or even at the point of impact of a single raindrop (Sharma *et al.*, 1991). Until recently, integrating researches in different scales (i.e. plot, field and catchment-scale) has been neglected because it is a difficult task (Boardman, 1996).

Table 1.1 Types of models (from Morgan, 1995)

Type	Description
Physical	Scaled-down hardware models usually built in the laboratory; need to assume dynamic similitude between model and real world.
Analogue	Use of mechanical or electrical systems analogous to system under investigation, e.g. flow of electricity used to simulate flow of water.
Digital	Based on use of digital computers to process vast quantities of data.
Physically-based	Based on mathematical equations to describe the processes involved in the model, taking account of the laws of conservation of mass and energy.
Stochastic	Based on generating synthetic sequences of data from the statistical characteristics of existing sample data; useful for generating input sequences to physically-based and empirical models where data only available for short period of observation.
Empirical	Based on identifying statistically significant relationships between assumed important variables where a reasonable database exists. Three types of analysis are recognised: - Black-box: where only main inputs and outputs are studied; - Grey-box: where some detail of how the system works is known; - White-box: where all details of how the system operates are known.

Therefore, prior to using a soil erosion model, where the model is to be used and why the specific model is appropriate should be considered carefully.

For error and uncertainty involved in modelling approaches, Oberkampf *et al.* (2002) suggest two definitions of uncertainty: aleatory and epistemic. Aleatory uncertainty refers to irreducible uncertainty, inherent uncertainty, variability and stochastic uncertainty. A probability or frequency distribution is generally used to quantify aleatory uncertainty, when sufficient information is available. Epistemic uncertainty refers to reducible uncertainty, subjective uncertainty and cognitive uncertainty. This is a source of non-deterministic behaviour that comes from lack of knowledge of the system or environment. This uncertainty can also be viewed as a potential inaccuracy in any phase or activity of the modelling process that is due to lack of knowledge.

Thus, even if we eliminate epistemic uncertainty by studying and obtain absolute knowledge, we will still not be able to predict future weather perfectly because of the aleatory uncertainty.

Oberkampf *et al.* (2002) defines error as a recognizable inaccuracy in any phase or activity of modelling and simulation that is not due to lack of knowledge. Using this approach, there are two types of errors: errors that are acknowledged and errors that are unacknowledged. Acknowledged errors are those inaccuracies that are recognised by the analysts. Unacknowledged errors are those inaccuracies that are not recognized by the analysts, but they are recognizable. The CLIGEN errors found by Yu (2000) can be seen as an example of unacknowledged errors (See Section 1.5.3.1).

Oberkampf *et al.* (2002) further suggest a comprehensive and new view of the general phases of modelling and simulation, consisting of six phases (Figure 1.2):

1. conceptual modelling of the physical system
2. mathematical modelling of the conceptual model

3. discretization and algorithm selection for the mathematical model
4. computer programming of the discrete model
5. numerical solution of the computer program model
6. representation of the numerical solution

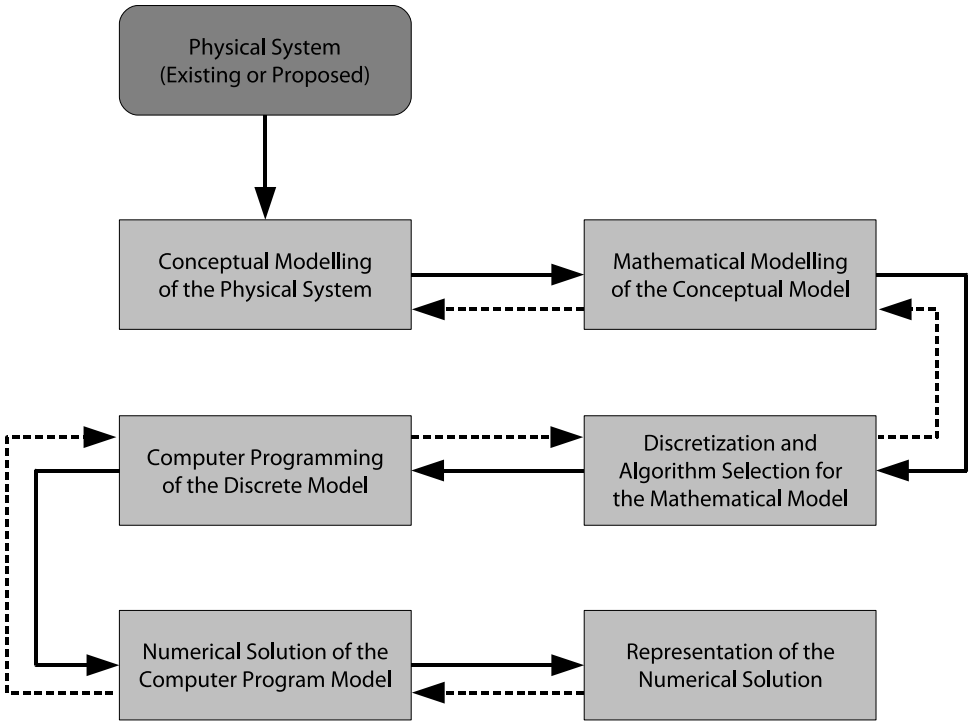


Figure 1.2 Proposed phases for computational modelling and simulation. (From Oberkampf *et al.*, 2002)

This framework is a synthesis of the reviewed literature, with three substantial additions compared to a more conventional viewpoint. First, it makes a more precise distinction between the system and the environment. Second, it places more emphasis on the distinction between aleatory and epistemic uncertainty in the analysis. Third, it includes a dominant element in the simulation of complex physical processes; the numerical solution of non-linear Partial Differential Equations (PDFs).

Conceptual modelling of of the physical system Conceptual issues are considered determining all possible factors.

Mathematical modelling of the conceptual model The primary activity of this phase is to develop detailed and precise mathematical models. The complexity of the models depends on the physical complexity of each phenomenon being considered, the number of physical phenomena considered, and the level of coupling of difficult types of physics. Emphasis on comprehensiveness in the mathematical model should not be interpreted as an emphasis on complexity of the model. The predictive power of a model depends on its ability to correctly identify the dominant controlling factors and their influences, not upon its completeness or complexity. A model of limited, but known, applicability is often more useful than a more complete model. Any mathematical model, regardless of its physical level of detail, is by definition a simplification of reality.

Discretization and algorithm selection for the mathematical model Converting the mathematical models into a form that can be addressed through computational analysis. Conversion of the continuum mathematics form of the mathematical model into a discrete, or numerical, model. Specifying the methodology that dictates which computer runs will be performed in a later phase of the analysis to accommodate the non-deterministic aspects of the problem.

Computer programming of the discrete model—modular approach Algorithms and solution procedures defined in the previous phase are converted into a computer code.

Numerical solution of the computer program model The individual numerical solutions are actually computed.

Representation of the numerical solution The representation and interpretation of both the individual and collective computational solutions. Basically this phase concerns how to present results for a group of specific audiences.

The erosion models used in the present research are reviewed in the next section. However, an additional model, the Universal Soil Loss Equation (USLE), is first discussed since this model embodies the basic concepts underpinning many more recent models.

1.5.2 Universal Soil Loss Equation (USLE)

The first attempt to develop a soil loss equation for hillslopes was that of Zingg (1940), who related erosion to slope steepness and slope length. Further developments led to the addition of a climatic factor based on the maximum 30-minute rainfall total with a 2-year return period (Musgrave, 1947), a crop factor to take account of the protection-effectiveness of different crops, a conservation factor and a soil erodibility factor, consecutively. All these factors were then incorporated together, modified and up-dated to the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978).

The USLE consists of six factors, which are simply multiplied together to estimate soil loss although there is substantial interdependence between the variables (Wischmeier and Smith, 1978):

$$A = R \times K \times LS \times C \times P \tag{1.1}$$

where A (tonnes·ha^{-1} yr^{-1}) is average annual soil loss, R (MJ·mm·hr^{-1} ha^{-1} yr^{-1}) is rainfall erosivity, K (t·hr·MJ^{-1} mm^{-1}) is soil erodibility, L (dimensionless ratio) is the slope-length factor, S (dimensionless ratio) is the slope-steepness factor, C (dimensionless ratio) is the cropping factor, and P (dimensionless ratio) is the conservation practice factor.

The rainfall erosivity factor (R) is related to the raindrop impact effect. R factor provides relative information on the amount and rate of runoff associated with the rain. The soil erodibility factor (K) is used to represent the differences of natural resistances of

soils to erosion. The slope length (L) and steepness(S) factors provide the topographic information that can affect the rate of energy dissipation. The cropping factor (C) is the ratio of soil loss from cropped field under specific conditions to the corresponding loss from tilled, continuous fallow conditions. The conservation practice factor (P) is the ratio of soil loss with a specific conservation practice to the corresponding loss with conventional slope tillage.

The USLE uses the empirical results of erosion studies conducted at many locations over nearly a half-century of research, including rainfall erosivity, soil erodibility, slope length, slope steepness, cropping and management techniques, and supporting conservation practices of more than 10,000 plot-years of data from about 50 locations in 24 states in the US (Wischmeier and Smith, 1978). The results were statistically analysed and the relationships between the factors incorporated into equation 1.1.

Both the strength and weakness of the USLE lie in its estimation of erosion as the product of a series of terms for rainfall, slope gradient, slope length, soil, and cropping factors. However, it does not account for any non-linear interactions between the factors (Wischmeier and Smith, 1978; Meyer, 1984).

Nicks (1998) suggests that USLE may be used to estimate soil loss on a storm by storm basis where incremental rainfall is available. Rainfall erosivity index (EI) for a rainfall event is calculated by

$$EI = R_{0.5} \sum (210 + 89\, log_{10} I) \tag{1.2}$$

where I is the incremental rainfall intensity and $R_{0.5}$ is the maximum storm 30 minutes rainfall. Individual storm erosion amounts may then be calculated with the USLE using this EI value to replace the R factor in equation 1.1, summed to give a yearly soil loss, and then averaged to produce a mean annual erosion estimate.

In contrast, Kinnell (2005*b*) points out important problems of predicting event

erosion using the USLE. One of the main problem described is that, in the USLE, there is no direct consideration of runoff even though erosion depends on sediment being discharged with flow, which varies with runoff and sediment concentration. Kinnell (2005*b*) concludes that the failure to consider runoff as a primary factor in the USLE is the factor that causing the USLE to produce the erroneous prediction of event erosion, which in turn leads to systematic errors in predicting average annual soil loss.

Since the introduction of the USLE to estimate soil loss, it has become the conservationists' primary tool for planning purposes (Diaz-Fierros *et al.*, 1987; Centeri, 2002). The USLE provides an ease of use and relatively reliable results, and requires only readily obtainable information in order to estimate average annual soil loss. However, Wischmeier (1976) warned about the problem of the misuse of the USLE.

The database for the original USLE is restricted to the US east of the Rocky Mountains (Wischmeier and Smith, 1978). The base is further restricted to slope where cultivation is permissible, normally 0 to 7°, and to soils with a low content of montmorillonite; it is also deficient in information on the erodibility of sandy soils (Wischmeier and Smith, 1978). It is important to note that, because the USLE was designed to estimate average annual soil loss from any specific field over an extended period, soil loss estimates for a specific year may substantially differ from the long-term average predicted by the equation (Wischmeier, 1976). Extrapolating the relationship beyond the database for the original USLE, therefore, should be conducted with care.

The basic concepts of the USLE were subsequently used and developed by some continuous simulation models. Some of these models are CREAMS (Chemicals, Runoff, Erosion, and Agricultural Management Systems) (Knisel, 1980), EPIC (Erosion-Productivity Impact Calculator) (Williams *et al.*, 1984), SWRRB (Simulator for Water Resources in Rural Basins) (Williams *et al.*, 1985), WEPP (Water Erosion Prediction Project) (Nearing *et al.*, 1989; Flanagan and Nearing, 1995).

1.5.3 Water Erosion Prediction Project (WEPP)

WEPP (Water Erosion Prediction Project) is a process-based model that describes the processes, such as infiltration and runoff, soil detachment, transport, deposition, plant growth, senescence, and residue decomposition, that lead to erosion (Flanagan and Nearing, 1995). The model takes four input files, climate, soil characteristic, slope, and crop management.

WEPP was developed by the USDA-ARS (United States Department of Agriculture-Agricultural Research Service) as a new-generation water erosion prediction technology for the routine assessment of soil erosion for soil and water conservation and environmental planning and assessment (Flanagan *et al.*, 2007). The development of WEPP was initialized with an intention to replace the 'long-used' USLE (See Section 1.5.2) (Nearing *et al.*, 1989; Flanagan and Nearing, 1995). WEPP no longer relies on factor values from the USLE, instead uses separate erodibility parameters for interrill (K_i) and rill erosion (K_r) (Flanagan and Nearing, 1995). In WEPP, rills are assumed to have a uniform rectangular cross-section with a uniform spacing of 1 metre. All rills are assumed to be equally hydrologically efficient (Flanagan and Nearing, 1995).

The steady state erosion component of WEPP is based on:

$$\frac{dG}{dx} = D_f + D_i \tag{1.3}$$

where G represents sediment load, x is the distant downslope, D_f is the rill erosion rate, and D_i is the interrill erosion rate. D_f and D_i are calculated on a per rill area basis. Rill erosion, D_f, is positive for detachment and negative for deposition, and calculated by:

$$D_f = D_c\left(1 - \frac{G}{T_c}\right) \tag{1.4}$$

where T_c is the transport capacity of flow in the rill, and D_c is detachment capacity of the rill flow and:

$$D_c = K_r(\tau_f - \tau_c) \tag{1.5}$$

where K_r is rill erodibility parameter, τ_f is flow shear stress acting on soil particles, and τ_c is the critical shear stress or rill detachment threshold parameter of the soil. Interrill erosion is given by:

$$D_i = K_i I_e \sigma_{ir} SDR_{RR} F_{\text{nozzle}} \frac{R_s}{\omega} \tag{1.6}$$

where K_i is the interrill erodibility, I_e is the effective rainfall intensity, σ_{ir} is the interrill runoff rate, SDR_{RR} is the sediment delivery ratio, F_{nozzle} is an adjustment factor to account for sprinkler irrigation nozzle impact energy variation, R_s is the rill spacing, and ω is the width. Interrill erosion is also expressed with baseline interrill erodibility as (Nicks, 1998):

$$D_i = K_{ib} I_e^2 C_C C_G \frac{R_s}{\omega} \tag{1.7}$$

where K_{ib} is baseline interrill erodibility, C_C is the effect of canopy cover on interrill erosion, and C_G is the effect of ground cover on interrill erosion. The hydrologic variables that drive the WEPP are the effective rainfall intensity and duration, the peak runoff rate, and the effective runoff duration.

The USLE erosion database could not be used directly for the WEPP parametrisation. Three field experiments on cropland, rangeland and forestland were conducted to determine parameters for K_r and K_{ib} given in equations 1.6 and 1.7. A total of 77 sets of plot data were collected (Nicks, 1998). Fixed rainfall intensity was applied to the plots using a rainfall simulator. A comprehensive model description is available in Flanagan and Nearing (1995).

Rainfall is represented in the WEPP with the double exponential function. A storm is described with four parameters, storm amount, average intensity, ratio of peak intensity

to average intensity, and time to peak intensity. A stochastic weather generator, CLIGEN (CLImate GENerator; Nicks *et al.*, 1995) is used to generate these storm precipitation inputs. More about CLIGEN is covered later in Section 1.5.3.1. WEPP then disaggregates these storm inputs into a single peak storm intensity pattern (time-rainfall intensity format) for use by the infiltration and runoff components of the model. (Flanagan and Nearing, 1995).

The WEPP model can be used for hillslope erosion processes (sheet and rill erosion), as well as simulation of the hydrologic and erosion processes on small watersheds. The hillslope mode predicts soil erosion from a single hillslope profile of any length. It can be applied to areas up to about 260 hectares in size. The watershed mode links hillslope elements of specified widths together with channel and impoundment elements. WEPP is designed to run on a continuous simulation but can also be operated for a single storm. A modified version of the hillslope WEPP has been developed for research purposes (Favis-Mortlock and Guerra, 1999; Favis-Mortlock and Savabi, 1996). This is designed to account for the effects of atmospheric CO_2 concentration changes on plant growth.

In this research, only hillslope mode of the WEPP (v2004.7) was used for continuous or single-event simulation, depending on the purpose.

1.5.3.1 CLIGEN

CLIGEN is a stochastic weather generator, which generates daily time series estimates of precipitation, temperature, dew point, wind, and solar radiation for a single geographical point, based on average monthly measurements for the period of climatic record (Nicks *et al.*, 1995). The estimates for each parameter are generated independently of the others (Nicks *et al.*, 1995).

In comparison to other climate generators, CLIGEN is better at preserving the low-order statistics of rainfall, temperature, and solar radiation on a daily, monthly,

and annual basis (Nicks *et al.*, 1995). Unique to CLIGEN is the capacity to simulate the three additional weather variables to characterize the storm pattern, namely storm duration, time to peak, and peak intensity, which are specifically developed for the WEPP simulation (Flanagan and Nearing, 1995).

CLIGEN stochastically generates four precipitation-related variables for each wet day, which are precipitation amount (mm), R, storm duration (hour), D, time to peak as a fraction of the storm duration, t_p, and the ratio of peak intensity over average intensity, i_p. Average intensity is defined as R/D. Although it is possible to calculate individual variables manually for each rainfall event, it is a labour intensive task to calculate the variables for multiple events.

CLIGEN requires observed precipitation statistics in order to generate these four precipitation-related variables (Table 1.2).

Table 1.2 Precipitation parameters required by CLIGEN to generate WEPP precipitation inputs (from personal communication with Bofu Yu, 2003)

Parameter	Description
meanP	Average precipitation (inches) on wet days for each month
sdP	Standard deviation of daily precipitation (inches) for each month
skP	Coefficient of skewness of daily precipitation (inches) for each month
P(W/W)	Probability of a wet day following a wet day for each month
P(W/D)	Probability of a wet day following a dry day for each month
MX.5P	Average maximum 30-min peak intensity (in/hr) for each month
TimePk	Cumulative distribution of time to peak as a fraction of the storm duration

Precipitation data required to derive the CLIGEN input parameters in Table 1.2 are time series of daily precipitation data and sub-daily precipitation data with a time intervals no greater than 30 minutes (personal communication with Bofu Yu, 2003). In principle, there is no need to distinguish these two types of precipitation data because sub-daily data can be accumulated to produce daily values. In practice, however, these two types of data usually come from two different sources. The coverage of the daily data, both in space and time, is much more extensive in comparison to sub-daily data at

short time intervals. In addition, the two types of data are normally stored in different formats. It is therefore useful to treat the two types of precipitation data separately.

CLIGEN (version 4.2) was previously released with WEPP version 2001.3. However, this version of CLIGEN had a major coding error and was modified substantially (Yu, 2000). CLIGEN (version 4.2) computed a ratio $\omega = R_{0.5}/R$, where both $R_{0.5}$ and R were rainfall depth (originally in inches). $R_{0.5}$ had been converted from inches into millimetres (mm), while R was not (Yu, 2000). The CLIGEN code was thus changed to correct this error. This however led to extensively increased storm durations.

To accommodate the correction of unit conversion error, it was necessary to incorporate two important modifications in the CLIGEN codes. First, a new algorithm to determine the monthly means of the maximum 30-min rainfall depth was implemented. Secondly, the parameter values for storm duration and the coefficient of variation for the ratio of the maximum 30-min rainfall depth to daily rainfall required in CLIGEN were estimated using the break-point rainfall data (Yu, 2000).

This error in the CLIGEN code has certainly affected the results from the earlier studies, which employed the previous versions of WEPP and CLIGEN to estimate soil loss (Truman and Bradford, 1993; Zhang *et al.*, 1995*a*,*b*, 1996; Baffaut *et al.*, 1996; Laflen *et al.*, 1997; Baffaut *et al.*, 1998; Favis-Mortlock and Guerra, 1999).

The version of CLIGEN at the time of writing is version 5.22564[1]. This is the version used in this research.

1.5.4 European Soil Erosion Model (EUROSEM)

EUROSEM is a dynamic distributed event-based model for simulating erosion, transport and deposition of sediment over the land surface by interrill and rill processes

[1]http://horizon.nserl.purdue.edu/Cligen/, April 2006

(Morgan *et al.*, 1998). The model has explicit simulation of interrill and rill flow; plant cover effects on interception and rainfall energy; rock fragment effects on infiltration, flow velocity and splash erosion; and changes in the shape and size of rill channels as a result of erosion and deposition (Morgan *et al.*, 1998). It can be applied to a small field and up to a small catchment.

EUROSEM requires a one-minute resolution breakpoint rainfall data for the storm. The model then computes, using the breakpoint rainfall data, the interception of the rain by the plant cover, the generation of runoff as infiltration excess, soil detachment by raindrop impact, soil detachment by runoff, transport capacity of the runoff and deposition of sediment. The model has a modular structure that aims to make further improvements of the model easier. The model considers the followings:

- the interception of rainfall by the plant cover
- the volume and kinetic energy of the rainfall reaching the ground surface as direct throughfall and leaf drainage
- the volume of stemflow
- the volume of surface depression storage
- the detachment of soil particles by raindrop impact and by runoff
- sediment deposition
- the transport capacity of the runoff
- frozen soils and stoniness

The flow chart for EUROSEM is shown in Figure 1.3.

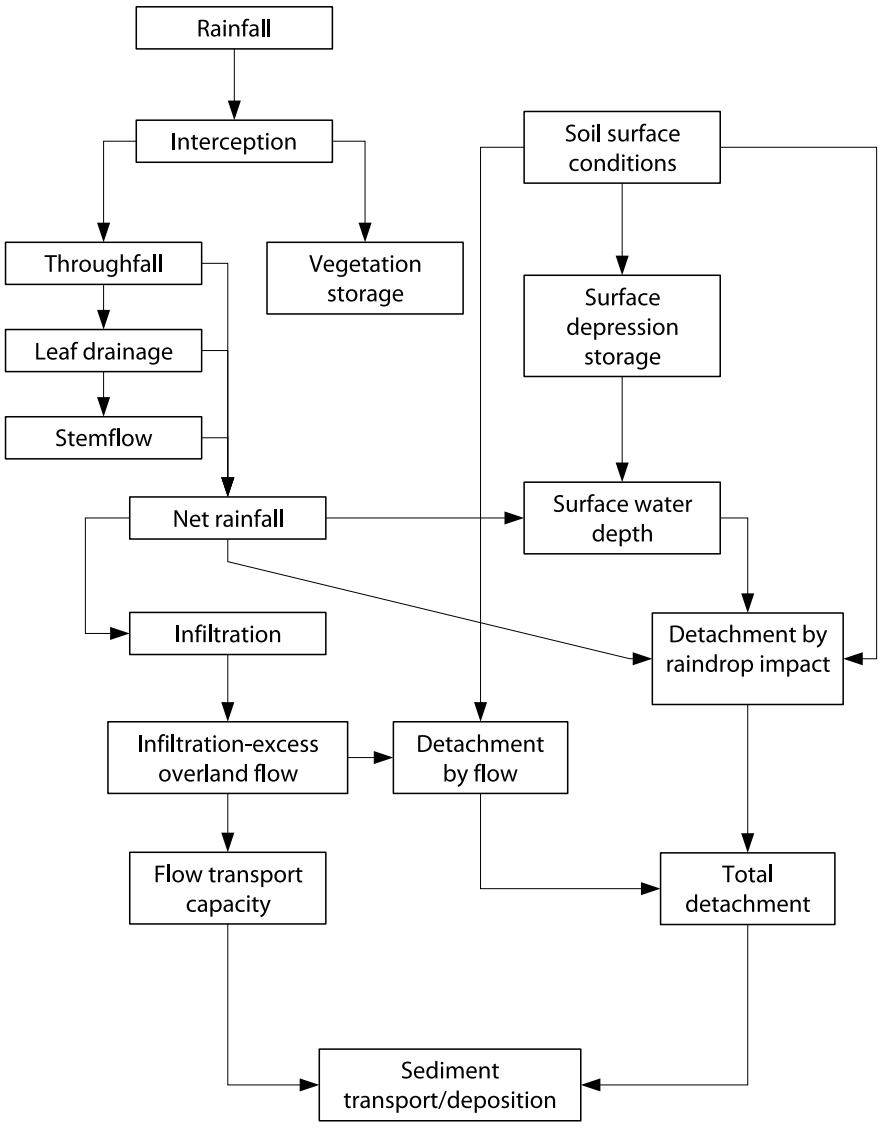


Figure 1.3 Flow chart of EUROSEM (from Morgan *et al.*, 1998)

Runoff generator and the water and sediment routing routines of EUROSEM are from another model called KINEROS (Woolhiser *et al.*, 1990). The volume of sediment passing a given point on the land surface at a given time is calculated by a mass balance equation:

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(QC)}{\partial x} - e(x,t) = q_s(x,t) \tag{1.8}$$

where C is sediment concentration (m^3/m^3), A is the cross sectional area of the flow (m^2), Q is the discharge (m^3/s), q_s is external input or extraction of sediment per unit length of flow ($m^3\ s^{-1}\ m^{-1}$), e is net detachment rate or rate of erosion of the bed per unit length of flow ($m^3\ s^{-1}\ m^{-1}$), x is horizontal distance (m), and t is time (s). The net detachment rate, e, is given as:

$$e = DR + DF \tag{1.9}$$

where DR is the rate of soil particle detachment by raindrop impact ($m^3\ s^{-1}\ m^{-1}$), and DF is the balance between the rate of soil particle detachment by the flow and the particle deposition rate ($m^3\ s^{-1}\ m^{-1}$).

The EUROSEM simulates erosion and deposition by calculating three main processes, soil particle detachment by raindrop impact, soil particle detachment by runoff, and transport capacity of the flow.

Soil particle detachment by raindrop impact Soil detachment by raindrop impact (DR) for time step (t_s) is expressed as a function of the kinetic energy of the rainfall at the ground surface, the detachability of the soil and the surface water depth:

$$DR = \frac{k}{\rho_s} KE e^{-zh} \tag{1.10}$$

where k is an index of the detachability of the soil (m^3/J), ρ_s is the sediment particle density (=2.65 Mg/m^3), KE is the total kinetic energy of the net rainfall at the ground

surface (J/m^2), z is an exponent taken as equal to 2.0 which varies between 0.9 and 3.1 (Torri *et al.*, 1987), and h is the mean depth of the surface water layer (m). The kinetic energy of the rainfall is the combined energy from direct throughfall and leaf drainage. The energy of the direct throughfall is computed using raindrop size distribution found by Marshall and Palmer (1948). The energy of the leaf drainage is based on a study by Brandt (1990).

Soil particle detachment by runoff Soil particle detachment by runoff is based on a theory proposed by Smith *et al.* (1995), and is given as:

$$DF = \beta w v_s (TC - C) \tag{1.11}$$

where DF is the rate of detachment of soil particles by the flow, β is a flow detachment efficiency coefficient ($\beta = 1$ when deposition is taking place and $\beta < 1$ for cohesive soils when DF is positive), w is the width of the flow (m), v_s is the setting velocity of the particles in the flow (m/s), TC is the sediment concentration in the flow at transport capacity, and C is the actual sediment concentration in the flow.

Transport capacity of flow EUROSEM uses two separate transport capacity relationships for rill and interrill flows. Rill and interrill transport capacities are based on Govers (1990) and Everaert (1991), respectively. The equation for rill transport capacity (TC_r) is expressed as:

$$TC_r = c(\omega - \omega_c)^{\eta} \tag{1.12}$$

where ω is unit stream power (cm/s) which is defined as $\omega = 10vs$ (v = mean flow velocity (m/s) and s = slope (%)), ω_c is a critical value of unit stream power (0.4 cm/s), and c and η are experimentally derived coefficients related to the median particle size of the soil.

Interrill transport capacity (TC_{ir}) is modelled as:

$$TC_{ir} = \frac{b}{\rho_s q}\left[(\Omega - \Omega_c)^{\frac{0.7}{n}} - 1\right]^{\kappa} \tag{1.13}$$

where b is a function of particle size, ρ_s is the sediment density (Kg/m^3), Ω is Bagnold's modified stream power, Ω_c is a critical value of Bagnold's modified stream power, n is Manning's n, and $\kappa = 5$. Sediment delivery to the rills is simulated depending on the transport capacity of the interrill flow.

Since EUROSEM uses a dynamic rather than steady-state approach used by WEPP, it gives a better understanding of the spatial and temporal distribution of runoff and erosion. However, the result of the model simulation may become considerably uncertain due to its process-based nature that requires detailed model parametrization (Quinton and Morgan, 1998). Particularly, EUROSEM requires high resolution rainfall data (ideally, 1-min breakpoint data), soil hydrological information, detailed surface geometry, and soil mechanical and vegetation characteristics. Because of the detailed requirements of the model, application of the model is greatly restricted to where such data are available.

Parsons and Wainwright (2000) found that because EUROSEM ignores small-scale heterogeneities in the infiltration characteristics of soil, the model generates delayed initiation times for runoff, so that predicted hydrographs showed the commencement of runoff later than observed. Such variabilities in the infiltration characteristics may be responsible for the comparatively rapid initiation of runoff on the plot. They also found that the subsequent soil detachment by runoff in interrill areas is overestimated by the model even though, according to the model document, detachment by flow should be negligible in interrill areas.

After personal communication (16 Jun 2004) with Anthony J. Parsons , it is noted

that EUROSEM may have a unit conversion error. The model document states that the flow depth (h) in equation 1.11 is in metres. However, a study by Torri *et al.* (1987) on which this equation is based indicates that the height is in millimetres (see Figure 2 in Torri *et al.* (1987)). Anthony J. Parsons suggests that the height is in centimetres rather than either metres or millimetres. If confirmed, this error would have major effects on EUROSEM's ability to estimate runoff and erosion.

The version of EUROSEM used in this research is 3.9 (14/12/1998), which is the current version of the model. It seems that the model development has been ceased for some time.

1.5.5 RillGrow

While the later two erosion models (i.e. WEPP and EUROSEM) reviewed previously are capable of realistically simulating rates of soil erosion, they (in common with all other present-day erosion models) have a number of conceptual shortcomings. For example, rills are considered to be equally spaced, with regular cross-sections, and to be of similar hydrological efficiency. In reality, rills are not necessarily spaced regularly and often have irregular cross-sections. Adjacent rills may also vary greatly in their ability to transport runoff and sediment (Favis-Mortlock, 1996). Additionally, while such models separately describe the different processes responsible for erosion in rill and interrill areas, they largely fail to acknowledge the physical link that exists between the processes operating in the two zones (Favis-Mortlock *et al.*, 2000).

The development of the RillGrow model (Favis-Mortlock, 1996, 1998*b*; Favis-Mortlock *et al.*, 2000; Favis-Mortlock and de Boer, 2003; Favis-Mortlock, 2004) started with a consideration of these shortcomings, and a question '*Is the initiation and development of hillslope rill systems driven by relatively simple rules acting on a much smaller scale?*'. To test this hypothesis, a self-organising dynamic systems approach was

used to simulate the initiation and development of a rill network on the bare soil of a small (e.g. plot-sized) hillslope area.

RillGrow is a single-event model, which generates realistic rill networks by simulating, on a grid of microtopographic elevations, the combined erosive action of overland flow moving between the cells of the grid. Surface water arrives, a single raindrop at a time, on random cells of the grid. Runoff moves over the grid following the steepest microtopographic gradient; as it moves, it erodes the soil surface by lowering the elevation of the soil's surface. Each change in elevation affects the routing of subsequent runoff: the result is a feedback loop in which flow patterns over the grid at any time depend on earlier flow patterns (and hence erosion), these flow patterns then condition subsequent flow patterns, and so on (Figure 1.4).

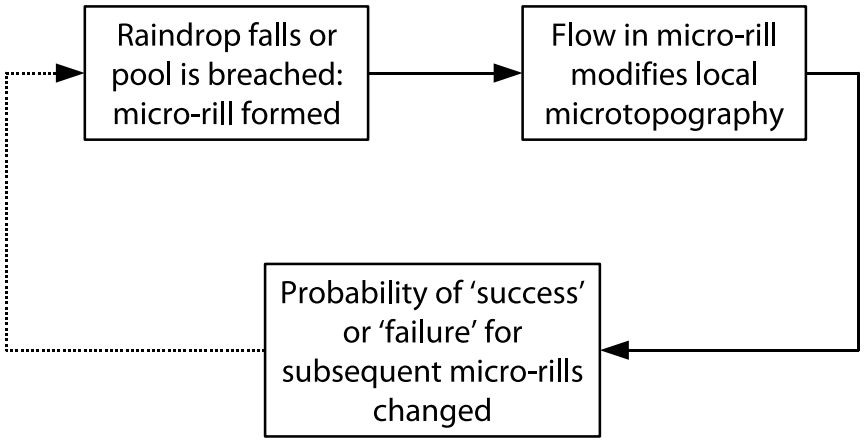


Figure 1.4 The conceptual feedback loop of RillGrow (From Favis-Mortlock, 1998*b*)

The first version of the RillGrow model was able to realistically simulate rill initiation and development, reproducing several features of observed rill systems (Favis-Mortlock, 1996, 1998*b*):

1. a narrowing of rill spacing with increased slope angle
2. an increased contribution of rill erosion with downslope distance
3. a non-linear increase of total erosion with slope steepness

4. an increase in rill depth below confluences and micro-rill piracy

However, RillGrow 1 has some important limitations. It ignores important process descriptions (e.g. infiltration, deposition), and the hydraulics of rill initiation are oversimplified. It also does not operate in a true time domain, since at any moment during the simulation, only a single 'packet' of overland flow is moving over the topographic grid. Infiltration is ignored, thus all water on the grid is assumed to be rainfall excess, and transport capacity is assumed to be infinite because no deposition can occur (Favis-Mortlock *et al.*, 2000). All these limitations meant that it was not possible to validate the model in a deterministic way, e.g. by comparing simulated and laboratory-produced rill networks.

A second version of the model ('RillGrow 2') was developed to overcome some of these limitations, and allow more rigorous validation (Favis-Mortlock *et al.*, 2000). In RillGrow 2, overland flow in effect moves concurrently between cells of the microtopographic grid. Such concurrency is not easy to achieve on a serial-processing computer, since only one instruction can be carried out at a time. Concurrent processing is simulated in RillGrow 2 in the following way: during a given timestep, outflow from each 'eligible' wet cell is routed in a random sequence which differs for each timestep. This variation in sequence is necessary to prevent any artefacts of flow pattern which might result from a fixed routing sequence. Over a sufficient number of timesteps, the model in effect operates in 'parallel', i.e. concurrently, in a true time domain.

RillGrow 2 also uses a refined set of basic rules for the routing algorithm (Table 1.3). A probabilistic expression by Nearing (1991), based on the random occurrence of turbulent bursts, is used to represent flow detachment. Sediment load is compared with transport capacity, which is calculated using stream power in an s-curve expression developed by Nearing *et al.* (1997). Deposition is estimated using the approach of Lei *et al.* (1998): this

Table 1.3 The main routing algorithm used in RillGrow 2 (From Favis-Mortlock *et al.*, 2000). Note that, while this set of rules does not change during the model simulation, the result of applying the rules to a given cell depends on the past history of elevation change both for that cell, and for adjacent ones.

For each iteration:

Drop raindrops on random cells on the spatial grid. Each drop makes (or adds to, if the cell is already 'wet') a store of surface water for that cell.

Go through all 'wet' cells in a random sequence (which is different each iteration). For each 'wet' cell, check whether sufficient time has elapsed for flow to have traversed the cell. If it has, then do the following:

- Find the adjacent cell which has the steepest downhill (i.e. outflow) energy gradient. Note that this adjacent cell may or may not be already 'wet'.
- Attempt to level the energy gradient between these cells by outflow of an appropriate volume, adding to (or creating) the store of surface water on the adjacent cell.
- Erode this cell (i.e. lower its soil-surface elevation) by an amount which depends on the outflow volume and velocity.
- If there are other adjacent cells with downhill energy gradients, process these as above.

assumes deposition to be a linear function of the difference between sediment load and transport capacity.

Infiltration is now simulated by RillGrow 2, however the approach used is still very simple (Favis-Mortlock, personal communication 2006). Splash redistribution is also represented, using the diffusion-based approach of Planchon *et al.* (2000), modified to include attenuation due to surface water depth (Favis-Mortlock, personal communication 2006). Additionally, a simple linkage is made between overall volumes of sediment detached or deposited by splash in any timestep, and volumes of sediment currently being transported by overland flow (Favis-Mortlock, personal communication 2006). The distribution of raindrop volumes is assumed to be normally distributed

(Favis-Mortlock, personal communication 2006).

In comparison to models such as WEPP and EUROSEM, RillGrow makes no explicit separation between rill and interrill areas. Soil erosion amount is calculated as the result of summation of soil losses from all areas. Flow velocities are so low on interrill areas that little detachment occurs as a result. On such areas, splash redistribution dominates.

Favis-Mortlock *et al.* (2000) observes that RillGrow 2 replicates the responses of RillGrow 1 including realistic rill spacing with respect to slope gradient. In addition, the simulated spatial patterns of erosion compare well with laboratory-based observations, as do total erosion, variation in rill depth, and time-series of runoff and soil loss. Braided or dendritic flow patterns can be made to emerge by varying rainfall intensity. At low rainfall intensities, however, the definition and stability of rill patterns is less well defined.

As originally constructed, RillGrow 2 assumed each storm to have a constant rainfall intensity. For the research described in this thesis, RillGrow 2 has been modified to use breakpoint rainfall data. This allows the model to simulate rill initiation and development and total soil loss, as affected by rainfall intensity changes (Favis-Mortlock, personal communication 2006).

Chapter 2

RESEARCH BACKGROUND AND OBJECTIVES

2.1 Background and Direction

> "If politics is the art of the possible, research is surely the art of the soluble. Both are intensely practical-minded affairs." (Peter Medawar (1915-1987) "The Act of Creation" in "New Statesman", 19 June 1964)

Before going into the aim of this research, it seems more appropriate to explain the scope and direction of this research first. In this way, readers may understand more clearly the research aim and rationale behind the approach used in this study.

When this research was first begun, the initial plan was to use the simulated future rainfall intensity output from RCM as input to one or more erosion models, in order to improve upon then-current forecasts of future erosion rates and eventually to develop a method to incorporate erosion model(s) into RCM.

However, after a number of test simulations with models at an early stage, it became apparent that RCM rainfall data could not (and still cannot) be used directly for erosion simulations. This is because RCM data do not hold sufficiently detailed information that can be used for erosion simulations, and were not reliable enough for this type of approach yet—and still they are not (Nearing, 2001; Michael *et al.*, 2005; O'Neal *et al.*, 2005). This means that, in order to use RCM data for the approach proposed initially, the data should be able to provide rainfall intensity information on a required scale with an acceptable level of confidence.

Thus, another route was taken to resolve this issue. In order to obtain rainfall data usable for erosion modelling in terms of scale and representable as future rainfall, observed rainfall data were analysed to determine trends of rainfall intensity. Once rainfall intensity trends are determined, probable scenarios of future rainfall intensity changes can then be built by applying the trend onto observed rainfall intensity.

Rather later, more problems were identified with selected erosion models, in that there were aberrant model responses to changes in a certain aspects of rainfall intensity (See Chapter 6). This implied that there were deficiencies in the process understanding on which the models are based. Thus, the original plan had to be put on hold until both, improved erosion models and more reliable RCM rainfall data, become available.

Accordingly, the focus of the research has evolved into the evaluation of the response of erosion models to rainfall intensity changes, and implicitly the process understanding on which the models are based, using arbitrary changes in rainfall intensity. In turn, this will assist in improving the performance of erosion models with respect to changes of rainfall intensity by highlighting where the current problem exists. Consequently, greater knowledge here will, once future changes in rainfall intensity become better known, improve our ability to estimate future rates of erosion.

2.2 Objectives and Rationales

The main objective of this research is to investigate:

- possible implications of climate change for future soil erosion with reference to rainfall intensity changes by analysing the response of erosion models to arbitrary rainfall intensity changes, and
- implicitly the process understanding on which the models are based.

To accomplish these aims, the research was carried out in three stages: *Rainfall Intensity and Erosion: Model Descriptions and Responses*, *Observed Rainfall Characteristics (and Intensity) of the Study Site* and *Implications for Model-based Studies of Future Climate Change and Soil Erosion*.

In the first stage, *Rainfall Intensity and Erosion: Model Descriptions and Responses*, three process-based erosion models, WEPP, EUROSEM and RillGrow, were used to investigate their responses (i.e. runoff and soil loss rates) to various rainfall intensity conditions. The process descriptions of these models were examined in regard to how they make use of rainfall intensity.

The reason for using multiple models is to minimize the probability of uncertainty that may increase when relying on a single model (IPCC Working Group I, 2001). The design purposes of erosion models varies from model to model, and so do their artefacts (Favis-Mortlock, 1998*a*; Jetten *et al.*, 1999). Thus, it is problematic to use only one model, unless there are some observational data that it can be compared to, as it is not possible to know to what extent the result from the model is unique to that model (Favis-Mortlock, 1998*a*; Jetten *et al.*, 1999).

For the same reason, it was suggested that, in the study of future climate change, one should not rely on a single GCM or RCM. This is also the case for the downscaling (Mearns *et al.*, 2003; Wilby *et al.*, 2004). In such studies, the same principle—more is better than one—is always in practice (Wilby *et al.*, 2004). This principle may equally be applied to the study of soil erosion modelling.

It would have been possible to use only two erosion models. However, this may have led to another problematic situation. For example, if two erosion models show contrasting results, it will be very difficult to decide which one to accept and which one to accept not—although it may still be debatable whether the resulting conclusion is applicable to the reality even when both models agree. A good answer to this dilemma may be found in an old fisherman's saying: "Never go to sea with two chronometers; take one or *three*." Therefore, *three* erosion models were used in this study.

Comparing results from three models, instead of one or two models, may increase our chances to relate modelling results back to the real world. If all three models show similar responses—even though the chances of incurring such result are slim—to rainfall intensity changes, the agreed results among three models may possibly be related to the real world (Araújo and New, 2007). More importantly, however, when any of the models disagree, further investigation should follow to look into the model equations, programmingg algorithms and codes in order to find out what may have caused such disagreement. By comparing outputs from these models, we could also identify their weaknesses and, in turn, improve them for future researches.

A primary purpose of these erosion models (i.e. WEPP, EUROSEM and RillGrow) is to simulate soil erosion. Even though each model has its unique way of simulating erosion processes, the main design purpose is the same; to simulate the real-world erosion processes. Erosion models are developed in order 1) to use them as important predictive tools for future or unmonitored landscapes; 2) to study how different factors

play a role in erosion; 3) to understand erosion processes; and in turn, 4) to minimise environmental issues caused by soil erosion. Because of these purposes, *ideally* all erosion models should be based on similar understanding of erosion, and simulate erosion similarly. This general idea was taken into account and it was hypothesised that the models selected for this research produce similar results when a given rainfall intensity was applied to them. Yet, the reality is somewhat different from the ideal, and one may still expect that the models may produce divergent responses (Favis-Mortlock, 1998*a*; Jetten *et al.*, 1999). However, it is important to investigate this diversity of model outputs in order to identify and improve areas where our understanding is limited.

> "The purpose of models is not to fit the data, but to sharpen the questions."
> (Samuel Karlin, Eleventh RA Fisher Memorial Lecture, Royal Society, 20 April 1983)

The above statement by Karlin highlights one of reasons why many models are used in numerical and analytical studies. In most cases, a model is based on knowledge that is limited by what we already know about the process. There can be a range of different understandings of the same processes—soil erosion processes in this case. These understandings are expressed as mathematical equations, and then translated into computing languages, and finally put together as a model with which our understandings of the processes can be tested. This provides us with a complete control over affecting parameters. Generally, it is not possible to gain complete control over affecting factors with field experiments or with laboratory experiments because modifying only one factor without altering other factors is not feasible. Using a model, an individual input parameter may be isolated, adjusted and investigated to find its effects on the overall erosion process, while keeping all the remaining parameters constant. Of course, this still does not guarantee a correct prediction by the model. However, this kind of approach helps to "sharpen the questions". More focused questions from modelling

studies may help to fill out, or rather to pinpoint the gap in our understanding of the processes. There have been several studies employing this type of approaches already (Favis-Mortlock and Boardman, 1995; Favis-Mortlock and Guerra, 1999; Pruski and Nearing, 2002*b*; Nearing *et al.*, 2005).

One more reason for using a model can be explained by the duration of experiments. According to Laflen (2003), in the case of erosion-plot experiments, the outcome may be very difficult to interpret unless the experiments were conducted for *a long period of time* because of high variability in the observational data. The result may not be significant unless the record is of sufficient length, treatments are greatly different, and a sufficient number of replicates is employed (Nearing *et al.*, 1999). Laflen (2003) stated "…it needs to be understood that these estimates [which are estimated using short periods of record] can have great error and that longer term records are needed to refine these estimates." He then suggested to design plots and collect the data "in such a way as to be able to use the data in evaluation of models and development of parameters that can be used to extrapolate results to the much wider climatic record than one can experience in a few years". Hence, using a model can be a good choice of method over observational experiments in some cases like above—and may well be the only method when estimating a long-term effect which cannot be observed. For example, in the study by Favis-Mortlock *et al.* (1997), EPIC (Erosion-Productivity Impact Calculator) was used to reproduce the past erosion processes on a hillslope in South Downs, UK from 7000 BP to the present day, in order to find out the major factors influencing past soil erosion. In a case like this, modelling is clearly the only possible choice. Modelling is also the only choice for the study on impacts of future climate or land-use changes on soil erosion (Favis-Mortlock and Boardman, 1995; Favis-Mortlock and Guerra, 1999; Pruski and Nearing, 2002*b*,*a*; Nearing *et al.*, 2005).

Therefore, the first stage of this study, using WEPP, EUROSEM and RillGrow, aims to investigate: 1) necessary information for rainfall intensity properties to simulate soil erosion, 2) responses of selected models to changes of rainfall intensity properties, 3) underlying processes of the models for computing rainfall intensity properties and 4) the applicability of the same models in the subsequent research stages.

In the second stage, *Observed Rainfall Characteristics (and Intensity) of the Study Site*, a series of observed high-resolution rainfall data were obtained to determine a trend of rainfall intensity changes at the research site in the South Downs, UK (Figure 3.1). One of the reasons for choosing this particular site is because the area has been extensively monitored for soil erosion since the late 1970s (Boardman, 1995, 2003), so that data availability of the site is therefore reasonably great. In addition, there is a well-established expertise about the area that can be referenced to the current research (Boardman, 1995; Favis-Mortlock and Boardman, 1995; Favis-Mortlock *et al.*, 1997; Favis-Mortlock, 1998*a*; Boardman, 2001, 2003). The datasets used here are temporally and spatially different; monthly 0.5° grid data, daily station data and tipping-bucket gauge data.

Moreover, as stated previously, this approach was taken because of the important issues discovered from RCM data. Probable scenarios of future rainfall intensity were created based on the *present-day* rainfall intensity trend. These present trends were also compared with GCM predicted data. The resulting scenarios were later used to make predictions regarding future erosion.

In short, the second stage aims to 1) provide a solution for the problem that have been identified with RCM rainfall data during the initial investigation of this research by analysing observed rainfall data in the various scales to determine rainfall intensity trends; 2) build scenarios of future rainfall intensity based on the *present-day* rainfall intensity trend, which may, in turn, be used for the final stage of the research.

In the last stage, *Implications for Model-based Studies of Future Climate Change and Soil Erosion*, the future rainfall intensity scenario from the second stage were used to estimate erosion rates using WEPP, one of the soil erosion models used in this research. WEPP is used here because it is a continuous simulation model, which is capable of simulating long-term erosion taking into account the factors such as the complex overlap of temporally and spatially diverse distributions of rainfall, erodibility, soil conditions, plant cover (Nearing, 2006).

The last stage of this thesis aims to 1) suggest the best possible way of investigating impacts of rainfall *intensity* changes on future erosion and 2) try to test out the suggested method with intensity-change scenarios constructed previously.

2.3 Some Questions To Be Answered

By carrying out the above stages, this research intends to address the following questions:

Question 1. What role does rainfall intensity play in the process descriptions which comprise erosion models?

Question 2. Assuming that we use a model to predict erosion rates under the future climate which may have different rainfall intensities from the present, what information do we need to make predictions in terms of both climate and process understanding?

Question 3. What do we know about future rainfall intensity? Does any trend exist in the present and past rainfall intensity at the study site? If so, is the trend consistent with future rainfall intensity predicted by climate models? If not, what must be done to estimate future rainfall intensity?

Question 4. Are we in a position to predict soil erosion under the future climate? If not, what must be done?

2.4 Expected Outcomes

Once all the research questions listed above have been answered, the following outcomes can be attained:

- Better understanding of the role of rainfall intensity in soil erosion model processes,
- Information requirements of rainfall intensity for soil erosion modelling,
- Probable estimation of future rainfall intensity, and
- Required criteria of rainfall data and erosion models for predicting future soil erosion.

Chapter 3

DESCRIPTIONS OF DATA, MODELS AND METHODS

3.1 Data

All of the dataset used for climate analyses, model parametrizations and erosion simulations are obtained from the South Downs, England, UK (Figure 3.1). The soil erosion in the area has been studied extensively for over 30 years (Boardman, 1995; Favis-Mortlock and Boardman, 1995; Favis-Mortlock *et al.*, 1997; Favis-Mortlock, 1998*a*; Boardman, 2001, 2003). Thus, data availability is very high in this area, and a well-established expertise in the characteristics of the area is available.

3.1.1 Rainfall Data

Reported mean annual rainfall of the South Downs, UK is between 750 and 1000 mm with an autumn peak (Potts and Browne, 1983). Mean annual temperature is 9.8°C with a January mean of 3.9°C and a July mean of 16.3°C (Potts and Browne, 1983).

Three temporally and spatially different observational rainfall datasets were acquired from the site (Table 3.1).

Observed monthly 0.5°×0.5° grid rainfall data (CRU TS 2.0—0.5°×0.5° Gridded Monthly Climate Data for Land Areas) for 100 years were obtained from Mitchell *et al.* (2004). Coordinates of the centre point of the study grid are 50.75° (Latitude) and -0.25° (Longitude).

Table 3.1 Precipitation data used in this study

Temporal Scale	Spatial Scale	Duration	Studied Rainfall Characteristics
month	0.5°×0.5° grid	100 years	amount
day	11 stations	10–99 years	7 indicators (see Table 3.7)
event[†]	3 stations	2–13 years	amount, duration, intensity

[†] Aggregated 1-min data originally from tipping bucket data

Daily rainfall amounts from 11 stations were obtained for the period of 1904 to 2004. Data durations are varied for each station (Table 3.2). Locations of individual daily stations are shown in Figure 3.1.

High resolution event rainfall data measured by tipping-bucket gauges were obtained from three stations—Ditchling Road, Southover and Plumpton—nearby the research site (Figure 3.2). Detection limit of the tipping bucket was 0.2 mm. Data duration from each station ranged from 2 to 13 years with some missing data between 1995 and 1998. This might have been because of vandalisms in the area, a defunct station or temporary gauge malfunctions (personal communications with Environment Agency on 1 March 2003). It should be noted that there are only a few rainfall stations which record event rainfall in the study region (Figure 3.2). Long term high resolution rainfall data with good quality is seldom available because of, for example, a large size of data file. However, quality of the data used here was reasonably good of capturing rainfall intensity details.

The detailed information about the daily and event data are summarised in Table 3.2.

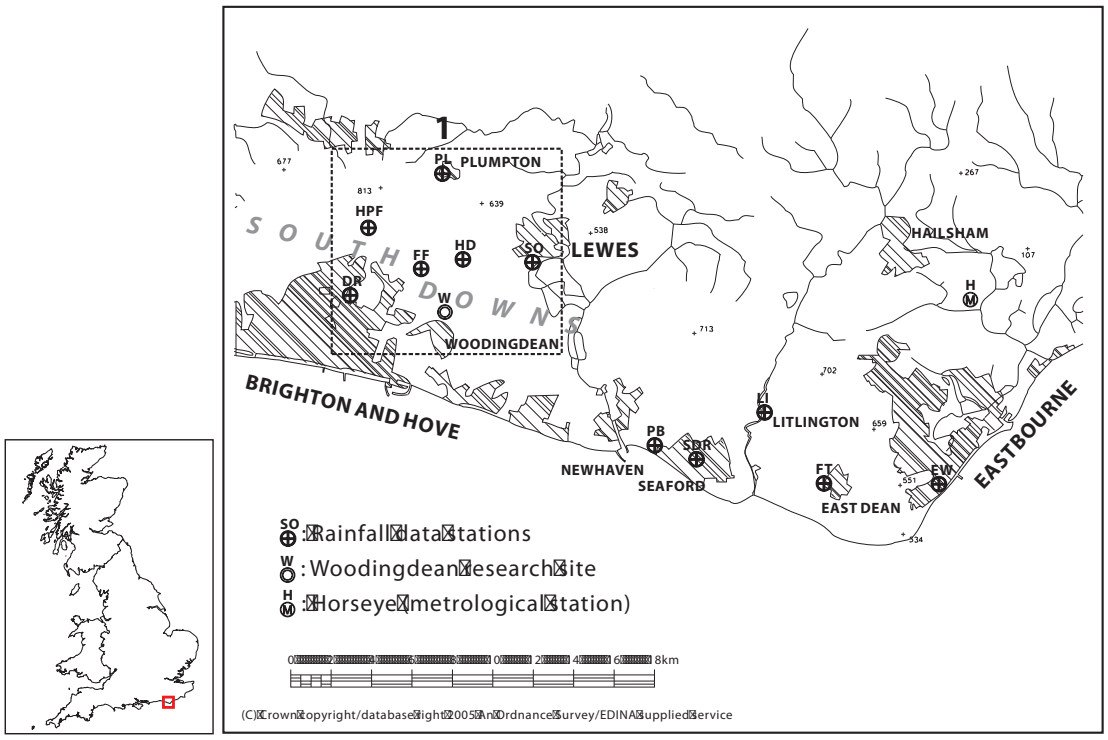


Figure 3.1 Locations of daily rainfall data stations. DR: Ditchling Road, SO: Southover, PL: Plumpton, SDR: Seaford D. Road, EW: Eastbourne Wilm., FT: Friston Tower, LI: Litlington, PB: Poverty Bottom, HPF: High Park Farm, HD: Housedean, FF: Falmer Farm, W: Woodingdean (soil, slope, crop management), H: Horseye (temperature); *dotted frame(1)* indicates the area shown in Figure 3.2.

Table 3.2 Details of rainfall data stations

Code	Station	Data type	Grid reference	Periods
DR	Ditchling Road	daily	TQ314076	1980–1989
SO	Southover	daily	TQ407093	1980–1998
PL	Plumpton	daily	TQ356136	1980–2000
SDR	Seaford D. Road	daily	TV491993	1980–2000
EW	Eastbourne Wilm.	daily	TV611980	1980–2000
FT	Friston Tower	daily	TV551982	1980–2000
LI	Litlington	daily	TQ523020	1980–2000
PB	Poverty Bottom	daily	TQ467002	1980–2000
HPF	High Park Farm	daily	TQ331115	1974–2004
HD	Housedean	daily	TQ369093	1967–2004
FF	Falmer Farm	daily	TQ342084	1904–2002
S	Southover	event	TQ407093	1993–2001[†]
D	Ditchling Road	event	TQ315077	1991–2003[‡]
P	Plumpton	event	TQ357135	2000–2002

[†] with missing data between Sep. 1996 to Jun. 1998

[‡] with missing data between Feb. 1995 to Sep. 1997

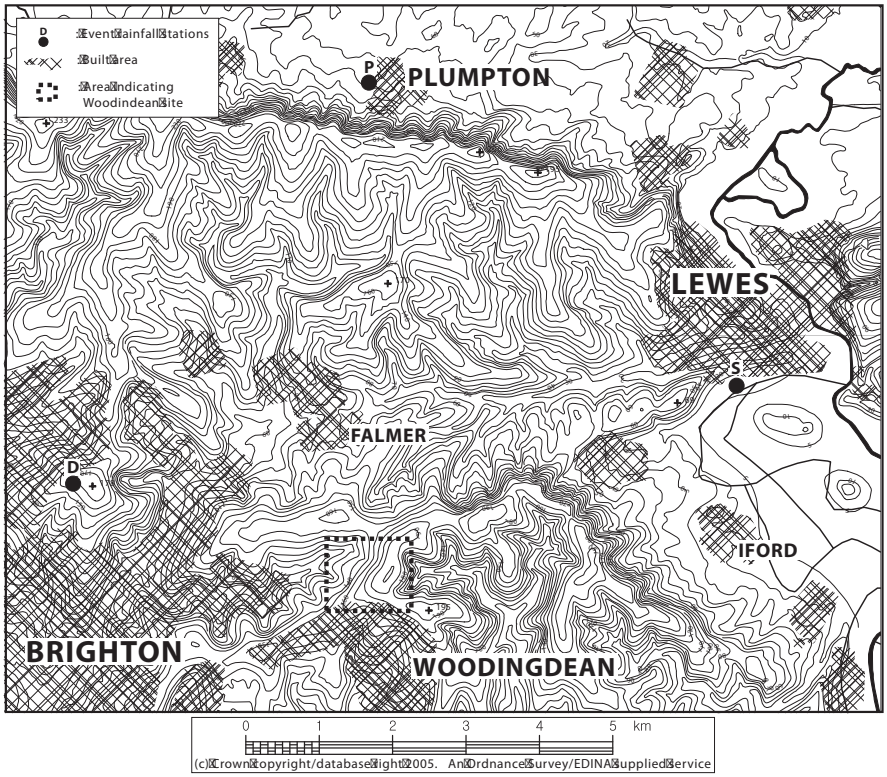


Figure 3.2 Locations of event rainfall data stations. *filled circles*: event rainfall data stations (S: Southover, D: Ditchling Road, P: Plumpton); Woodingdean site is indicated by *dotted frame* (see Figure 3.3 for the detail)

3.1.2 Other Data

3.1.2.1 Soil

Other input data, such as soil properties and slope profiles, were either directly acquired from previous studies (Favis-Mortlock, 1998*a*) or calibrated as shown in Table 3.4. Unless it was critically necessary, all the data were kept unchanged. This minimizes unknown effects which may occur because of changing other erosional factors, and also permits the present research to concentrate on the effect of rainfall intensity changes.

The erosion simulation site is 7.7 ha in size, and is located at Drove Road, Woodingdean (NGR: TQ358069): this is in the UK South Downs, about 6 km southwest of Lewes (Figure 3.3). Soil, slope and crop management details are obtained from this site.

Figure 3.3 Woodingdean site. The arrows indicate approximate downslope direction. Each letter (D-L) denotes hillslope profiles used for model simulations.

The soil in the area is shallow (around 20 cm to chalk) and stony silty rendzina of

the Andover series (Jarvis *et al.*, 1984). The Andover silt loams of the South Downs are both stony and prone to crusting. All the soil input parameters are summarised in Table 3.3 and Table 3.4.

Table 3.3 Andover soil details (From Favis-Mortlock, 1998*a*)

	Layer			
	1	2	3	4
Depth to bottom of layer (mm)	150.0	200.0	300.0	1000.0
Sand (%)	18.9	18.9	25.0	25.0
Clay (%)	3.5	3.5	24.0	24.0
Organic matter (%)	7.0	4.8	2.2	1.2
Cation exchange capacity (meq/100 g of soil)	45.0	39.0	30.0	14.0
Coarse (Rock) fragments (% vol)	38.1	50.0	90.0	90.0

Values for WEPP's parameters for effective hydraulic conductivity, together with values for its three erodibility parameters, were subjectively adjusted following the suggestions by Favis-Mortlock (1998*a*) (Table 3.4). The parameters for interrill and rill erodibility (K_i and K_r) were reduced, while the critical shear stress parameter τ_c was increased. The value for the base line effective hydraulic conductivity parameter K_b was also increased. All the adjustments were taken from Favis-Mortlock (1998*a*) with the exception of critical shear stress parameter τ_c which was recalibrated to 6. This was done in order to meet the recommended value of maximum τ_c by the WEPP documentation. All calibrated values were constrained to remain within the recommended ranges in WEPP documentation (Flanagan and Nearing, 1995).

3.1.2.2 Management

A typical crop management practice for the area is continuous growing of winter wheat. The typical timing of tillage operation for the area is shown in Table 3.5.

Table 3.4 Hydrological and erosional parameter values (After Favis-Mortlock, 1998*a*)

	Uncalibrated Hydrological and erosional parameters	Calibrated Hydrological and erosional parameters
Effective hydraulic conductivity of top soil layer (mm/hr)	2.1[a]	3.0[a]
Interrill erodibility K_i (kg s/m^4)	5502700	2000000
Rill erodibility K_r (s/m)	0.0871	0.0050
Critical shear stress τ_c (N/m^2)	3.5	6.0[b]

[a] 'baseline' effective hydraulic conductivity for WEPP (K_b)
[b] adjusted to 6 which is a maximum value for cropland τ_c

Table 3.5 Tillage operation timing at Woodingdean site (From Favis-Mortlock, 1998*a*)

Operation	Date
Chisel plough	20 August
Harrow	15 September
Drill (Winter wheat)	28 September
Roll	1 October
Harvest	29 July

3.1.2.3 Topography

Slope angles in the site range from 12 to 20%, with a convexity toward the centre. The site was divided into nine sub-areas for modelling, approximately down the line of greatest slope, which faces a northwesterly direction (Figure 3.3). The length of each slope varies from 125 to 180 metres, and width is 50 metres for all the slopes.

3.1.2.4 Temperature

Daily temperature records for 1990–2000 were obtained from Horseye Station (NGR: TQ627083) (Figure 3.1). The distance of this station from the study site is about 25 km. This data set was used in this study since no other data set was available from the region at that time. Average annual maximum and minimum temperature are 14.9°C (SD: 5.5°C) and 6.6°C (SD: 4.9°C), respectively.

3.2 Justification for Erosion Model Selection

As the research aims to investigate impacts of extreme rainfall events, all soil erosion models used in this research should be able to simulate a single erosion event. WEPP, EUROSEM and RillGrow were chosen because of this reason. All three models are capable of simulating single events while WEPP may also be used for continuous simulations (Table 3.6).

There are two more reasons why these models were used. One is that they use different approaches to erosion simulations and rainfall intensity. WEPP, for example, estimates soil erosion using steady-state approach (Equation 1.3) while EUROSEM employs a dynamic approach using a mass balance equation (Equation 1.8). Both models also consider rill and interrill areas separately and use different equations for describing processes in two areas. In terms of rainfall intensity, WEPP uses rainfall intensity as effective rainfall intensity for estimating interrill erosion. In EUROSEM rainfall intensity is considered as a function of kinetic energy of raindrops which act as detachment agents of soil particles. RillGrow, on the other hand, is based on a self-organising dynamic system to simulate the initiation and development of a network of rills. RillGrow also does not consider rill and interrill areas separately. All three models are described previously (Section 1.5). The other reason why these models were used is that they are originally designed for different simulation scales, temporally and spatially. Table 3.6 summarises some features of these three models.

Comparing the outputs from three erosion models could reveal strengths and weaknesses of their approaches to soil erosion. In turn, this investigation may provide improved insights on the behaviour of the models in relation to rainfall intensity changes.

WEPP was selected partly because it has been widely used and studied (Zhang *et al.*,

Table 3.6 Summary of the erosion models used in this research

	WEPP	EUROSEM	RillGrow
Spatial Scale	small catchment, hillslope, individual field	small catchment, hillslope, individual field	small field, laboratory plot
Reference	Nearing *et al.*, 1989 Flanagan and Nearing, 1995	Morgan *et al.*, 1998	Favis-Mortlock, 1998*b*
Purpose	event-based erosion transport and deposition long-term simulation	event-based erosion transport and deposition	rill initiation and development
Approach	Steady-state	Dynamic	Self-organising dynamic
Required Data	soil erodibility, slope profile and crop management	soil erodibility, surface characteristics and plant cover	detailed surface micro- topography, soil type and rainfall intensity
Rainfall Intensity	Yes (effective)	Yes (kinetic energy)	Yes
Simulation Type	single event or continuous	single event	single event

1996; Baffaut *et al.*, 1998; Favis-Mortlock and Guerra, 1999; Pruski and Nearing, 2002*a*,*b*; Flanagan *et al.*, 2007), so there is a substantial amount of information to compare it with. Moreover, when WEPP was developed, it was implemented with an unique method (or sub-model) of describing and utilizing rainfall data, called CLIGEN. This feature has been described previously in Section 1.5.3.1. The second model, EUROSEM, was selected because it was developed with European conditions in mind, as its name may imply (i.e. *EUR*opean *S*oil *E*rosion *M*odel) (See Section 1.5.4 for review). In this regard, EUROSEM may provide a good comparison to WEPP, which has been developed mainly with datasets collected from the USA (Flanagan *et al.*, 2007). Lastly, RillGrow was employed in the later stage of the research in order to generate stronger consensus from an additional model. RillGrow's unique approach (i.e. a self-organising dynamic systems approach) to soil erosion simulation (See Section 1.5.5) is also another reason for the selection. RillGrow simulates erosion on a finer scale using iterations of erosion estimations by a single raindrop at a time. This also gives a good comparison to the former two models.

3.3 A Brief Overview of Research Method

This research aims to discover how rainfall intensity changes will affect the soil erosion rate in the future, using soil erosion models. The research method involves data acquisition, such as observed rainfall properties and soil properties, configuring erosion models, and sensitivity tests of erosion models. The simulation carried out for the sensitivity test mainly employs a univariate method.

Three soil erosion models, WEPP (Water Erosion Prediction Project), EUROSEM (EURopean Soil Erosion Model), and RillGrow were used to simulate runoff and erosion rate under various rainfall intensity conditions. Effects of temporal resolution of rainfall data on runoff and soil loss generations are investigated to identify requirements of

rainfall intensity information for erosion simulations. Two extreme rainfall events; one with highest rainfall intensity and the other with highest rainfall amount, were selected from the tipping-bucket rainfall data. Tipping-bucket data for the events are then aggregated into a range of different temporal “scales". This is done by the discretization of tipping-bucket data into rainfall data that have a range of time-steps (i.e. 1, 5, 15, 30 and 60min). Runoff and soil loss rates were simulated using three models with these rainfall input data. An additional rainfall event, which has both wet and dry phases during the storm period, was selected. Two rainfall input data were prepared from this event data; one without any alteration and the other that is aggregated into a continuous storm by removing dry phases during the storm. Runoff and soil loss rates were simulated using three models with these two additional rainfall inputs. This was done to investigate effects of the dry phase within a storm on soil erosion. Impacts of various rainfall intensities patterns on soil erosion were also studied using rainfall data from a designed storm. Four different storms that have increasing, increasing-decreasing, decreasing and constant rainfall intensity were prepared for erosion simulations. Rainfall amounts for all four storms were kept the same while the intensities vary.

To understand observed trends of rainfall intensity changes, three observed precipitation data (i.e. Monthly 0.5° grid data, daily station data and tipping-bucket gauge data) were acquired from the South Downs, UK. Monthly 0.5° grid data for 100 years were analysed, firstly, to draw outlines of long term rainfall trends in the area. Daily precipitation data from 11 stations for the various observational periods (i.e. 9–93 years) in the area were then analysed, in terms of:

- daily rainfall amount,
- number of raindays,
- simple daily intensity index,
- number of raindays with rainfall amount ≥10 mm, and

- number of raindays with rainfall amount ≥20 mm.

This gave more detailed information about the trends of rainfall in the region than that obtained from monthly 0.5° grid data. Lastly, even greater detailed rainfall trends were studied using tipping-bucket collected rainfall data from three stations over the period of 2–13 years. This kind of high resolution data provides very detailed information on the patterns of the rainfall amount and intensity.

Likely future soil erosion rates were estimated only using WEPP, as the other two models are not designed for continuous long term simulations. A hundred year-long weather is generated by the WEPP's climate component called CLIGEN (CLImate GENerator) as a control climate dataset. Rainfall intensity was then increased proportionally from the control data by changing rainfall duration, keeping rainfall amount constant. Runoff and erosion rates were simulated using these climate data.

3.3.1 Statistical Methods for Trend Investigation

Statistical methods used in this research are briefly summarized here.

Simple Linear Regression Linear regression function ($y = \alpha + \beta x$) was assumed where rainfall related indicators (Table 3.7) as dependent variables (y) and time as a independent variable (x). The regression coefficient (β) might be used to detect trends in time series of the indicators. The Student's t-test was used to test whether the trend is statistically significant.

Mann-Kendall's Test Mann-Kendall's test is a non-parametric test for the detection of trend in a time series. This is primarily used because it has no linearity assumption. Since the first proposals of the test by Mann (1945) and Kendall (1975), covariances between Mann-Kendall statistics were proposed by Dietz and Killeen (1981) and the test was

extended in order to include seasonality (Hirsch and Slack, 1984), multiple monitoring sites (Lettenmaier, 1988) and covariates representing natural fluctuations (Libiseller and Grimvall, 2002).

The Mann-Kendall rank correlation (Mann, 1945; Kendall, 1975) is sensitive to both linear and non-linear trends. This is a non-parametric method and is based on ranking of a time series, using only the relative ordering of ranks (Press *et al.*, 1996). It does not give any information about the magnitude of the trend in the actual time series but rather gives a significance of the trend, and information on the direction of the observed trend (i.e. upward, downward or unchanged).

Kolmogorov-Smirnov test The two sample Kolmogorov-Smirnov test is used to determine if two distributions differ significantly. The K-S test is a non-parametric test that tests differences between two distributions. The K-S test has the advantage of making no assumption about the distribution of data. Its null hypothesis is that the two samples are distributed identically. The test is sensitive to differences in location, dispersion and skewness of the distribution (Sokal and Rohlf, 1995).

3.4 Observed Rainfall Characteristics Of The Study Area

3.4.1 Introduction

As stated previously, it became apparent at the early stage of this research that RCM rainfall data could not (and still cannot) be used directly for erosion simulations. Although RCMs and empirically downscaled data from GCMs allow projections to be made at a finer scale than GCMs, RCM projections still vary greatly between models in the same way as GCMs and empirical downscaling does not attempt to correct any biases in the data from the GCMs. Even with a finer scale than GCMs, RCM data do

not hold sufficiently detailed information of rainfall intensity that can be used directly for erosion simulations, and were not reliable enough for this type of approach yet—and still they are not (Nearing, 2001; Michael *et al.*, 2005; O'Neal *et al.*, 2005). That is why this part of research was carried out.

Moreover, using outputs from a model as inputs to another model will increase the level of uncertainty because there may be compound errors originated from both models. For example, when RCMs generate future rainfall data, these rainfall data are in a wrong scale, that is a larger scale than what is needed for erosion simulations. Also, rainfall intensity data that have been obtained from these RCM generated rainfall data will be in a wrong scale. This scale mis-match induces the use of downscaling to make the data usable for soil erosion modelling. During these processes, the level of uncertainty will increase process after process. Therefore, using observed rainfall data for erosion simulations may be more beneficial than using RCM data. It certainly is easier to track errors from known sources such as observed rainfall data, too.

The limitation of using observed data would be that it needs correctly scaled data to begin with and needs reasonably long data duration to be able to pick up seasonal variations at least, if not greater. Also, it should be remarked that this approach is to create scenarios of future rainfall which are based on present-day rainfall, not future rainfall. Thus, this approach assume that future rainfall trends stay the same as present-day rainfall trends.

In this chapter, three different scales of observed rainfall records were analysed to find the rainfall intensity trend—Monthly 0.5° grid rainfall, daily station rainfall and event rainfall measured by tipping-bucket gauges. The descriptions of these data are covered in Section 3.1.

3.4.2 Method

All three datasets described previously (Table 3.1) were analysed to find out rainfall intensity trends in the area using simple linear regression and Mann-Kendall (M-K) rank correlation. Monthly 0.5° grid rainfall data and daily station rainfall data were used without any conversion. Event rainfall data recorded by a tipping-bucket gauge are analysed. Tipping-bucket gauge rainfall data were aggregated into 1-min rainfall data prior to use. Rainfall amount, duration and daily maximum 1-min peak intensity were investigated using 1-min event rainfall data.

Kundzewicz and Robson (2004) suggested a number of tests for trend detection: Spearman's rho, Kendall's tau/Mann-Kendall test, Seasonal Kendall test, Linear regression and other robust regression tests. Hannaford and Marsh (2006) also used three methods (i.e. M-K rank, Spearman's rho and linear regression) to assess trends in UK runoff and low flows. They found a good agreement between the detection rate of trends between the three trend-testing methods. More studies have observed a high degree of equivalence between M-K rank and Spearman's rho tests (Yue *et al.*, 2002) and M-K rank and linear regression (Svensson *et al.*, 2005)

Yue *et al.* (2002) investigated the power of M-K rank and Spearman's rho. They found that both have similar power in detecting a trend to the point of being indistinguishable in practice. Yue *et al.* (2002) said "The power of M-K rank test depends on the pre-assigned significance level, magnitude of trend, sample size, and the amount of variation within a time series. That is, the bigger the absolute magnitude of trend, the more powerful are the tests; as the sample size increases, the tests become more powerful; and as the amount of variation increases within a time series, the power of the tests decrease. When a trend is present, the power is also dependent on the distribution type and skewness of the time series."

Thus, two trend test methods, that are linear regression and M-K rank, are used in this section.

The trends in daily rainfall characteristics were investigated. Rainfall related indicators were calculated to determine rainfall characteristics (Table 3.7). Daily rainfall intensity is obtained by dividing the monthly rainfall amount by the number of raindays.

Table 3.7 Rainfall intensity indicators

Indicator	Definition	Unit
RR	Precipitation sum	mm
RR1	Number of wet days (RR ≥ 1 mm/day)	days
SDII	Simple daily intensity index: $\frac{\text{total rainfall amount for wet days (RR} \geq 1 \text{ mm/day)}}{\text{number of wet days}}$	mm/day
R10mm	No. of days with precipitation ≥ 10 mm/day	days
R20mm	No. of days with precipitation ≥ 20 mm/day	days
R10p†	Ratio of days with precipitation ≥ 10 mm/day ((R10/RR1)×100)	%
R20p†	Ratio of days with precipitation ≥ 20 mm/day ((R20/RR1)×100)	%

† Additional indicators, which are not listed in the European Climate Assessment & Dataset project (ECA&D) website. Complete list of indicators and their definitions are available at http://eca.knmi.nl/indicesextremes/indicesdictionary.php

Any year with partial records were discarded to minimize the effects from missing data (Table 3.8). The records of the last year of each station were also discarded as they are incomplete. For example, daily rainfall data from Falmer Farm (FF) were considered only for 1904–1996 discarding the records for 1997 and 1999 with missing data. Three more years (1998, 2000 and 2001) were discarded from all the stations because of the discontinuity resulted in by removing missing data periods. Also, there was a problem with 2000 rainfall because they were recorded as weekly total rather than daily total.

There are some missing data periods for event data from Ditchling Road (DR) and Southover (SO) as well. All the years with any missing data period was discarded. Thus, only 9, 4 and 2 year-long data were used from Ditchling Road (DR), Southover (SO) and Plumpton (PL) stations, respectively.

Table 3.8 Daily Rainfall Stations and Record Details

Code	Station Name	Periods*	Studied Periods*
DR	Ditchling Road	1980–1989 (10)	1980–1988 (9)
SO	Southover	1980–1998 (19)	1980–1997 (18)
PL	Plumpton	1980–2000 (21)	1980–1998 (19)
PB	Poverty Bottom	1980–1998 (19)	1980–1997 (18)
SDR	Seaford D. Road	1980–2000 (21)	1980–1999 (20)
EW	Eastbourne Wilmington	1980–2000 (21)	1980–1999 (20)
FT	Friston Tower	1980–2000 (21)	1980–1999 (20)
LI	Litlington	1980–2000 (21)	1980–1999 (20)
HPF	High Park Farm	1974–2004 (31)	1975–2003 (29)
HD	Housedean	1967–2004 (39)	1968–2003 (37)
FF	Falmer Farm	1904–2002 (99)	1904–1996 (93)

* ( ): Number of years

In this research, daily rainfall is defined as the total rainfall that fell in a 24-hour period beginning at 9:00 am, and the day is indicated by the date on which the period begins. For example, precipitation of 5.2 mm on 29 July 2001 means that the cumulative amount of precipitation between 9:00 am, 29 July 2001 and 9:00 am, 30 July 2001 was 5.2 mm. A "midnight to midnight" approach is rarely used for rainfall data records because of practical difficulties for observation. British Summer Time (BST) is not considered here. A wet day is also defined when the amount of daily precipitation is equal to or more than 0.2 mm.

All no-rain periods within a day were removed from 1-min event rainfall data, and rainfall durations were calculated as effective durations. It has been assumed that there is only one storm on a given wet day, and rainfall is continuous during that storm. This approach was used for CLIGEN to parametrise daily rainfall storm. Rainfall intensity was calculated by dividing rainfall amount by the effective duration.

3.4.3 Monthly Precipitation

Observed mean annual rainfall amount from the studied 0.5° grid during 1901–2000 period is 902.6 mm. Annual rainfall amount which is calculated from monthly grid data show no significant trend (Figure 3.4).

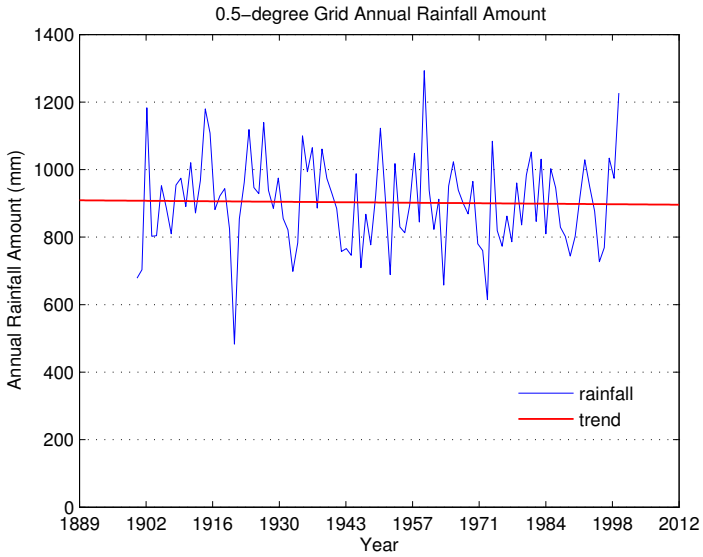
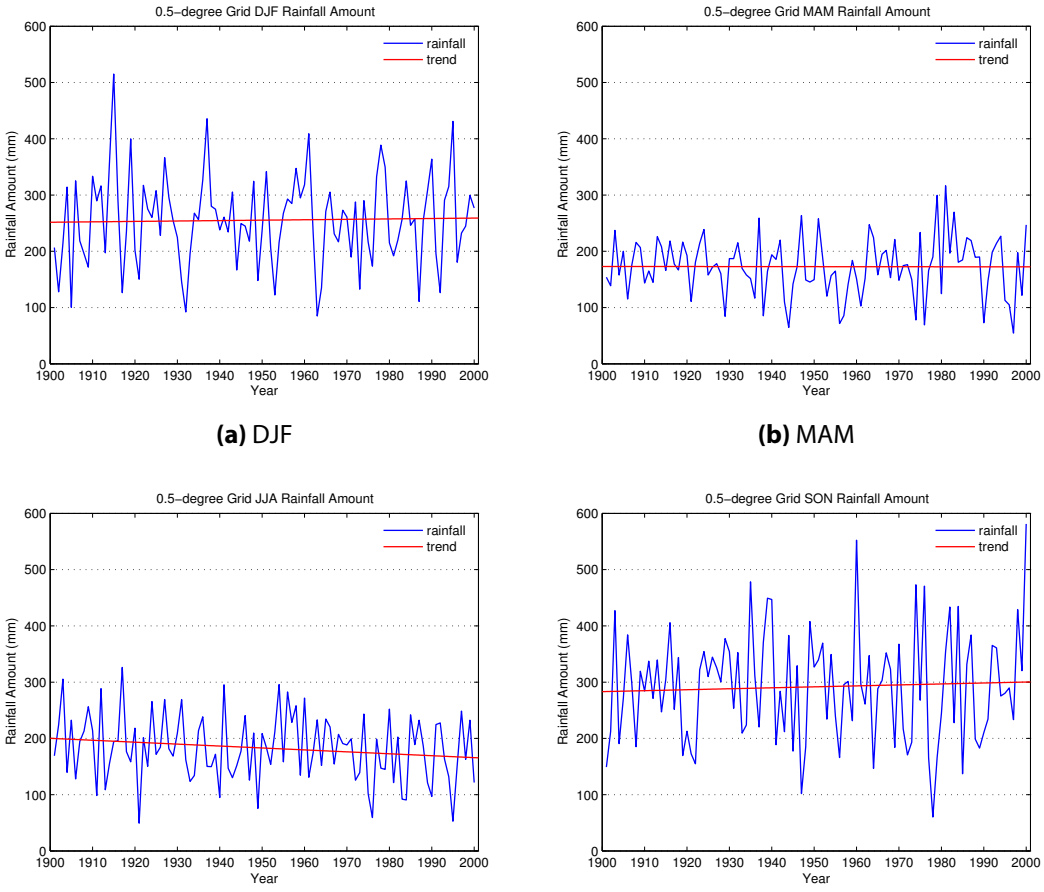


Figure 3.4 Annual rainfall amount trend of monthly grid data

There is no statistically significant trend in seasonal rainfall amounts (Figure 3.5).

Monthly rainfall amount pattern shows more rainfall in autumn and winter months with a peak in November, and less rainfall in spring and summer months (Figure 3.6). Monthly analysis of the grid data shows more detailed monthly trend in rainfall amount. Rainfall amounts in March show a statistically significant ($p < 0.05$) decreasing trend over 1981–2000 by both simple linear regression and Mann-Kendall's test.

Rainfall amounts in July have a decreasing trend throughout the whole data period (1901–2000) (Figure 3.7).



(a) DJF **(b)** MAM

(c) JJA **(d)** SON

Figure 3.5 Seasonal rainfall amount trend of monthly 0.5° grid data

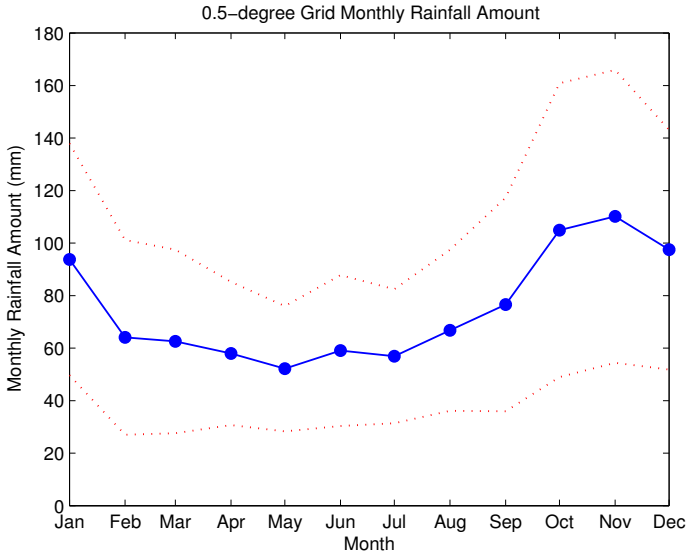


Figure 3.6 Average monthly rainfall patterns of monthly grid data. Dotted lines indicate standard deviation with 95% confidence level.

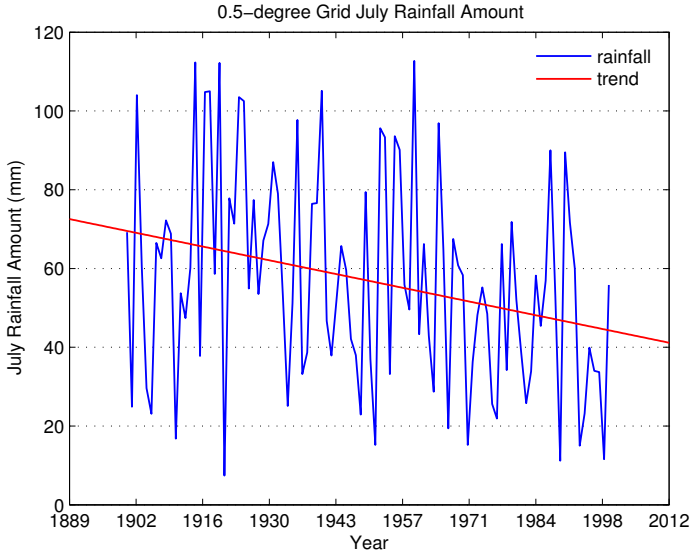


Figure 3.7 July rainfall amount trend over 1901-2000

3.4.4 Daily Precipitation

Annual rainfall amount from Poverty Bottom (PB), Friston Tower (FT), Eastbourne Wilmington (EW), Litlington (LI) and Seaford D. Road (SDR) stations are significantly different from those of Plumpton (PL) or High Park Farm (HPF), for example. This may be because of the distance from each other (see Figure 3.1) although all stations are placed in the 0.5° grid square.

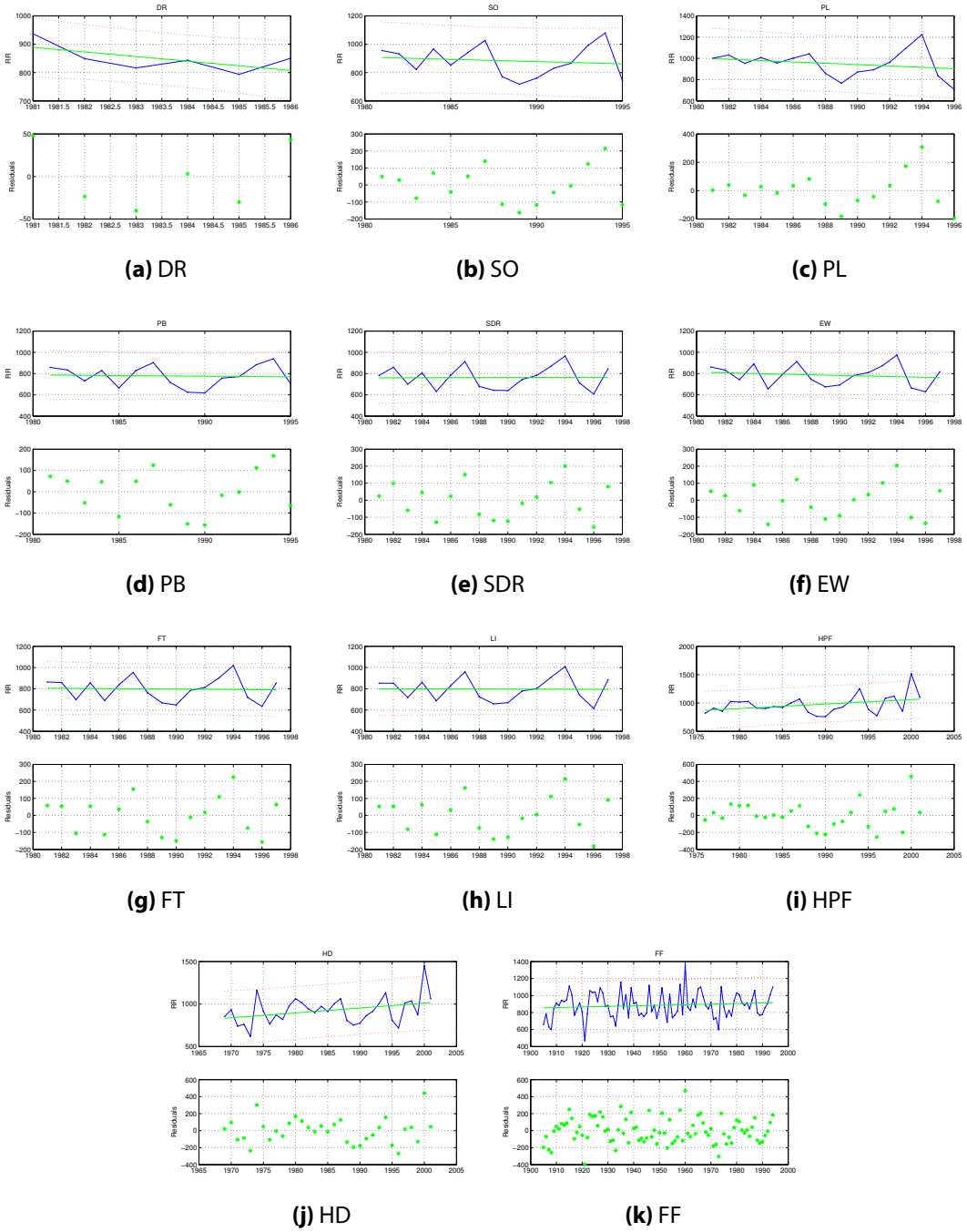
Rainfall Amount (RR) All the station show no statistically significant trend in annual rainfall amount. This result agrees with that of monthly 0.5° grid rainfall data.

For all the stations except Ditchling Road (DR), High Park Farm (HPF) and Housedean (HD), monthly rainfall amount in March showed statistically significant downward trends over the last two decades. The similar downward trends are observed with rainfall amounts in July for the last decades with the exception of DR, PB, HPF and HD stations. For longer periods, the trend of monthly rainfall amount is inconclusive. This broadly agrees with the results from the 0.5° grid data analysis. For monthly 0.5° grid data, July months showed a decrease in rainfall amount.

Number of Wet Days (RR1) The number of wet days per year decreased at PL and FF stations (M-K, $p < 0.05$) (Figure 3.9). Although not all the stations showed statistically significant annual trends, the ones with significant annual trend in the number of wet days show downward trends in the number of wet days over the data periods.

The month of March shows significant decreasing trends in the number of wet days per month over 1980–1999. The month of July also shows decreasing trend in the recent decade.

Simple Daily Intensity Index (SDII) As expected, PL & FF again showed a significant annual trend in SDII. The rest of the stations showed no significant results. FF station



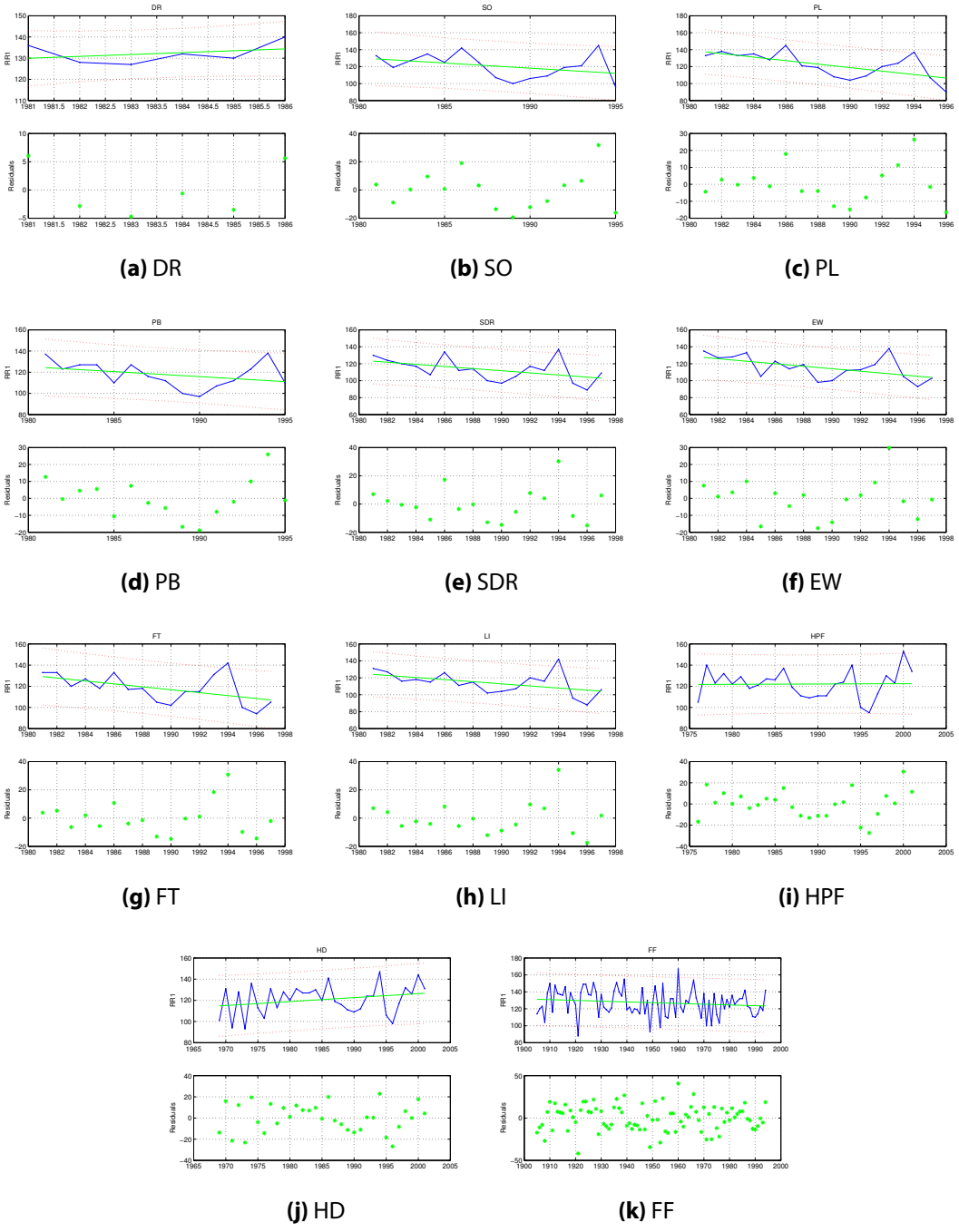
(a) DR **(b)** SO **(c)** PL

(d) PB **(e)** SDR **(f)** EW

(g) FT **(h)** LI **(i)** HPF

(j) HD **(k)** FF

Figure 3.8 Trends of annual rainfall amount (RR) at daily data stations



(a) DR **(b)** SO **(c)** PL

(d) PB **(e)** SDR **(f)** EW

(g) FT **(h)** LI **(i)** HPF

(j) HD **(k)** FF

Figure 3.9 Trends of number of wetdays (RR1) at daily data stations

showed upward annual trends in SDII throughout the data periods (Figure 3.10). All the cases with significant trends exhibited increasing trend of annual SDII.

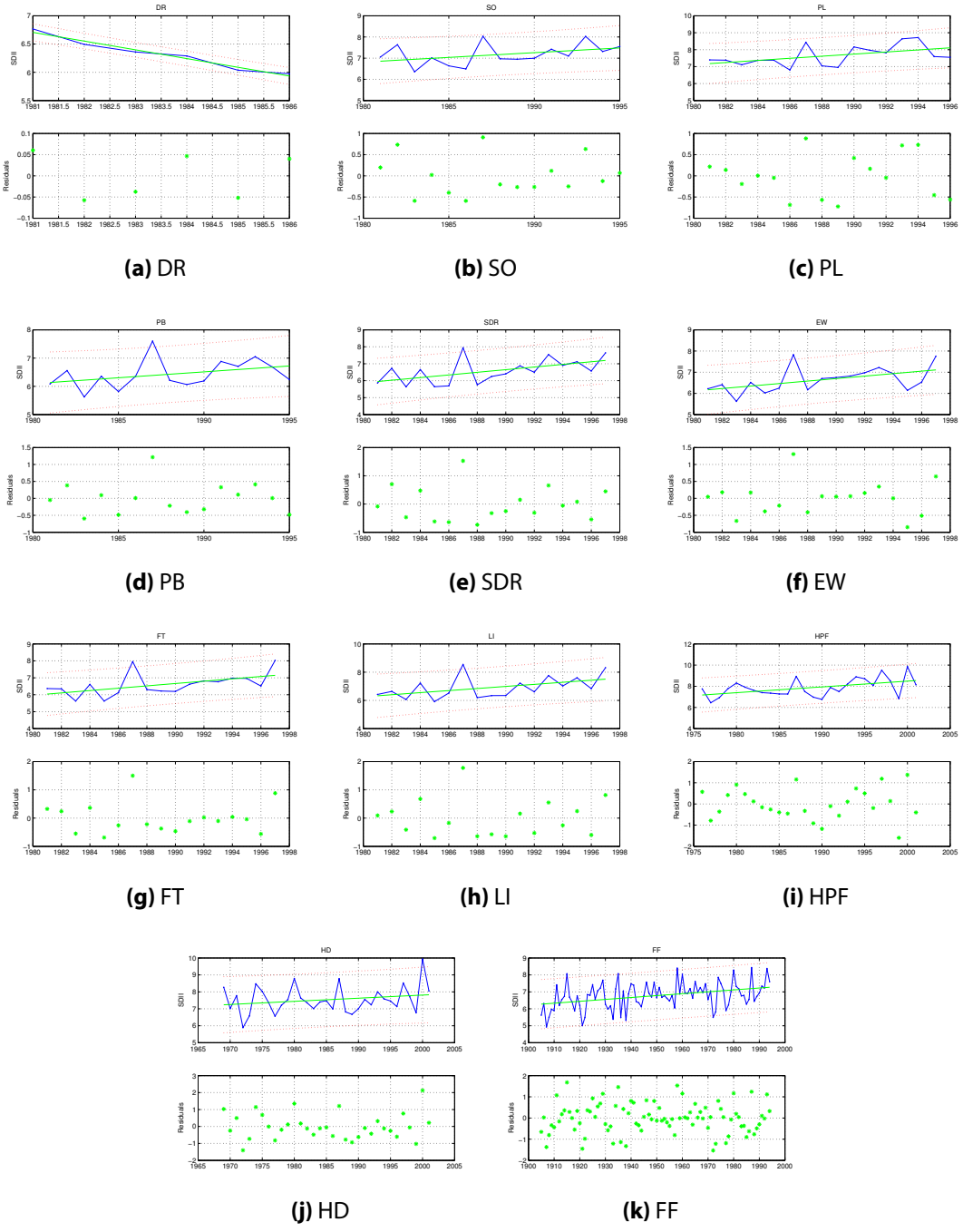
Number of Days with Precipitation Amount ≥ 10 mm (R10mm) Annual trends of number of wet days with precipitation amount greater than 10 mm (R10mm) from the studied stations are at variance. Only Falmer Farm Station shows a statistically significant upwards trend for the 1971–1996 period (M-K, $p < 0.05$) (Figure 3.11). PL ($p < 0.05$) and FF ($p \ll 0.05$) show a statistically significant increasing trend in the annual ratio of number of wet days with rainfall amount greater than 10 mm (Figure 3.12k).

Number of Days with Precipitation Amount ≥ 20 mm (R20mm) No station shows a significant trend in the annual number of wet days with rainfall greater than 20 mm. A trend in the annual ratio of number of wet days with rainfall amount over 20 mm was not detectable as well (Figure 3.13).

3.4.5 Event Precipitation

The result of the trend investigation with event rainfall data showed no significant trend in amount, duration and intensity. The trends are either not detectable or inconclusive. Thus, monthly patterns of amount, duration and intensity have been investigated. The observed daily rainfall amount, duration and intensity—1-min peak intensity—are shown in Figure 3.15, Figure 3.16 and Figure 3.17, respectively.

The highest daily rainfall amount is 133.8 mm which fell on 11 October 2000 at Plumpton. This rainfall is also the longest rainfall event which lasted for 443 minutes as a effective duration, which is over 7 hours (Figure 3.16). The average intensity of the event was 18.1 mm/hr.



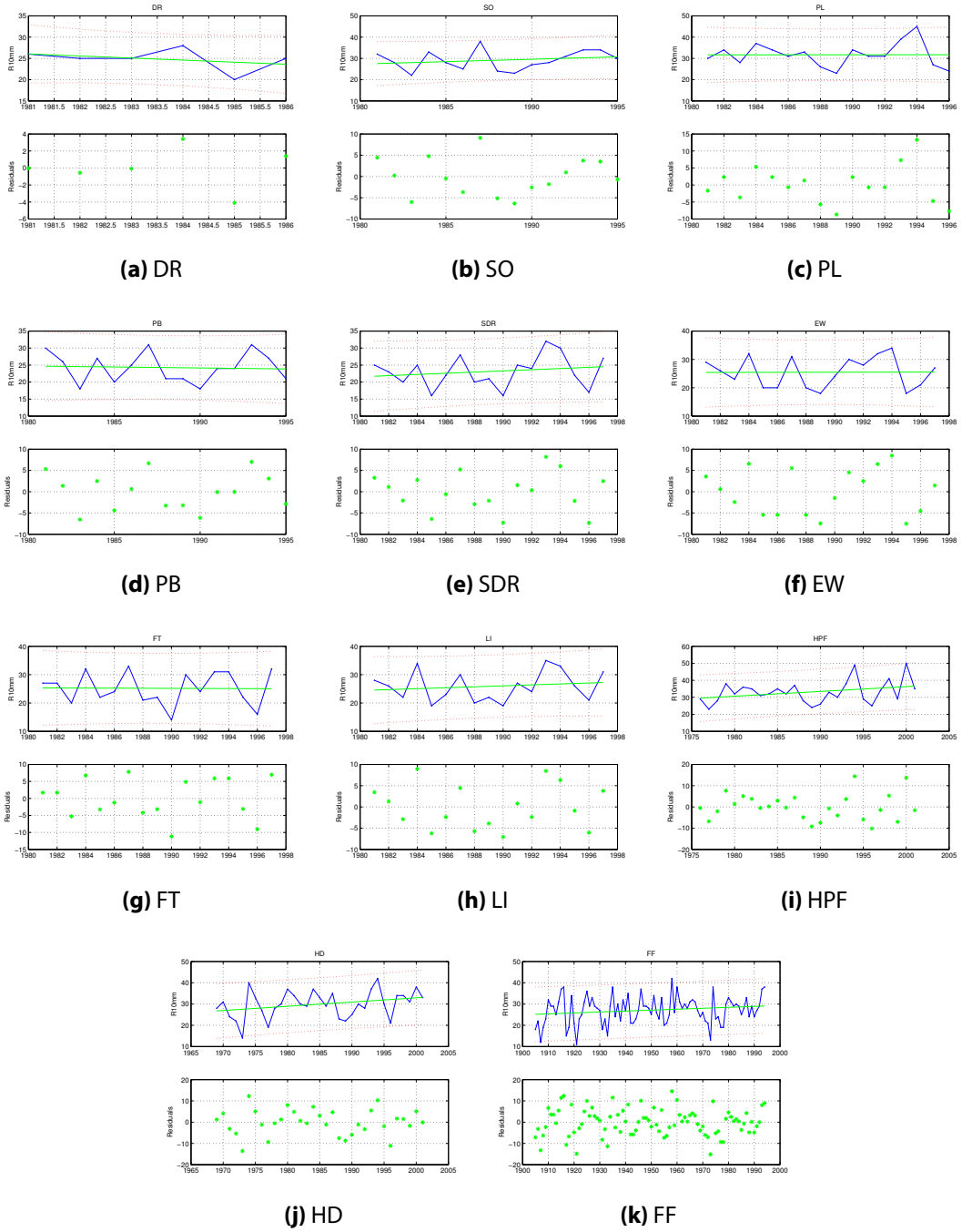
(a) DR **(b)** SO **(c)** PL

(d) PB **(e)** SDR **(f)** EW

(g) FT **(h)** LI **(i)** HPF

(j) HD **(k)** FF

Figure 3.10 Trend of annual simple daily intensity index (SDII) at daily data stations



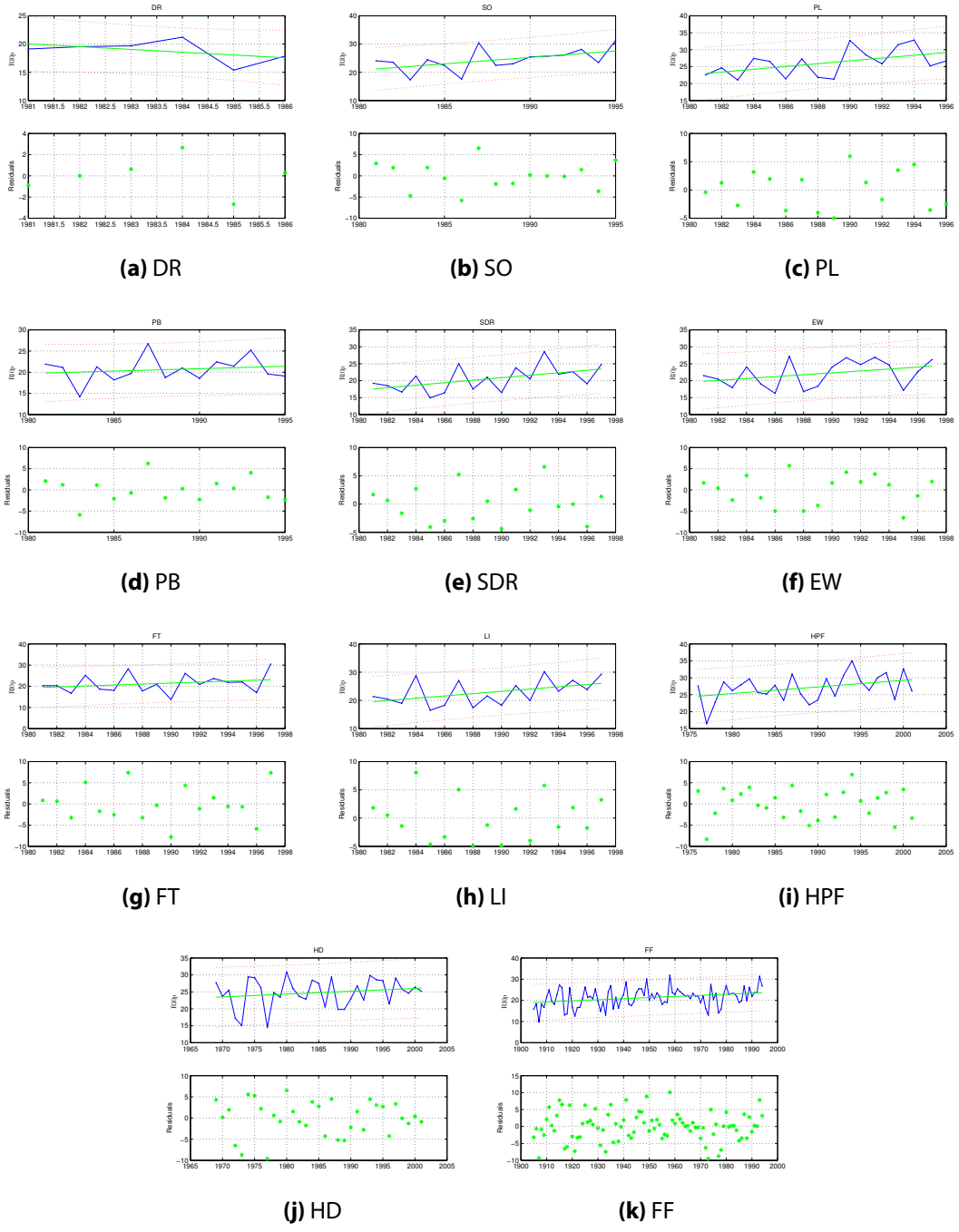
(a) DR **(b)** SO **(c)** PL

(d) PB **(e)** SDR **(f)** EW

(g) FT **(h)** LI **(i)** HPF

(j) HD **(k)** FF

Figure 3.11 Annual number of wet days with rainfall amount ≥ 10 mm at daily data stations



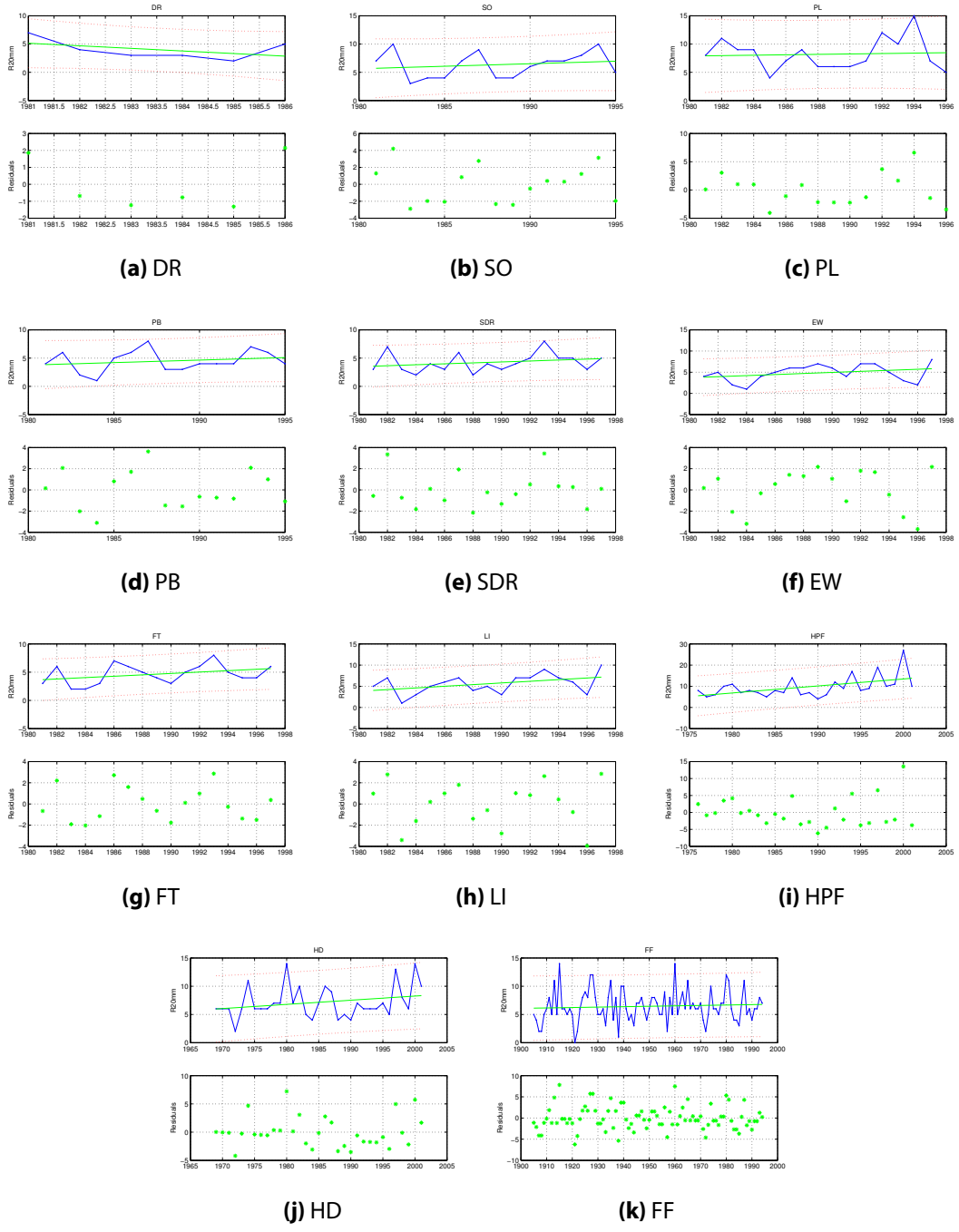
(a) DR **(b)** SO **(c)** PL

(d) PB **(e)** SDR **(f)** EW

(g) FT **(h)** LI **(i)** HPF

(j) HD **(k)** FF

Figure 3.12 Annual % of wet days with rainfall amount ≥ 10 mm at daily data stations



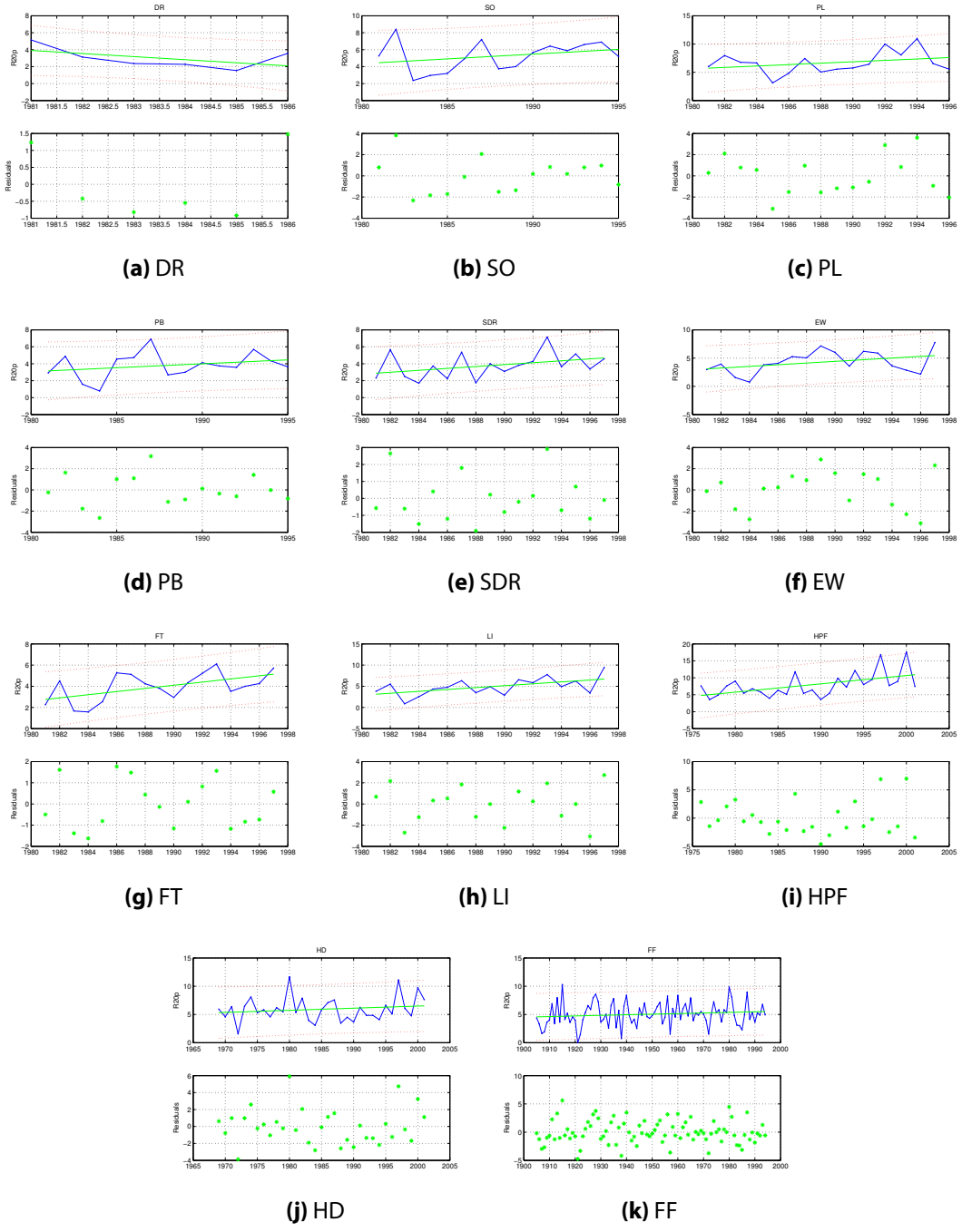
(a) DR **(b)** SO **(c)** PL

(d) PB **(e)** SDR **(f)** EW

(g) FT **(h)** LI **(i)** HPF

(j) HD **(k)** FF

Figure 3.13 Annual number of wet days with rainfall amount ≥ 20 mm at daily data stations



(a) DR **(b)** SO **(c)** PL

(d) PB **(e)** SDR **(f)** EW

(g) FT **(h)** LI **(i)** HPF

(j) HD **(k)** FF

Figure 3.14 Annual % of wet days with rainfall amount ≥ 20 mm at daily data stations

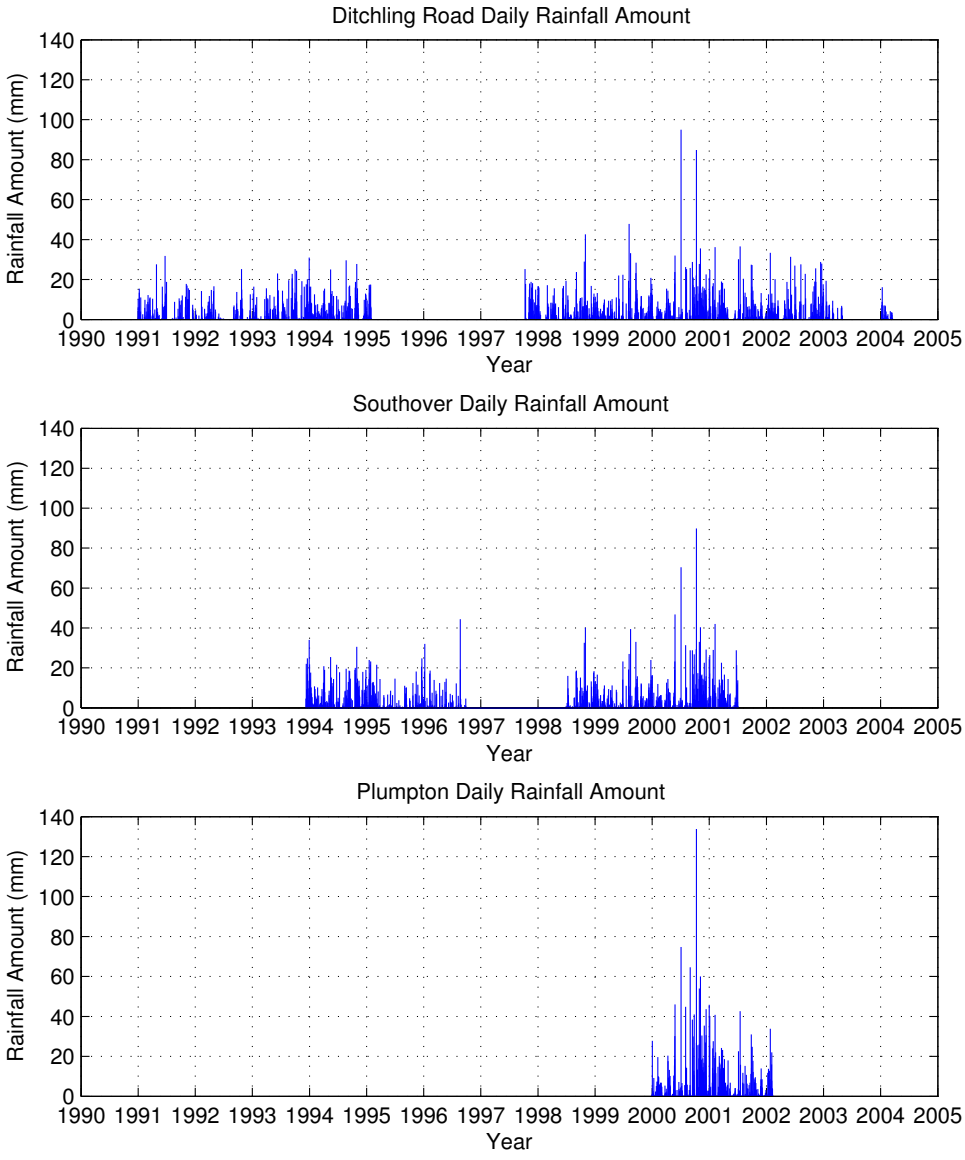


Figure 3.15 Observed daily rainfall amount

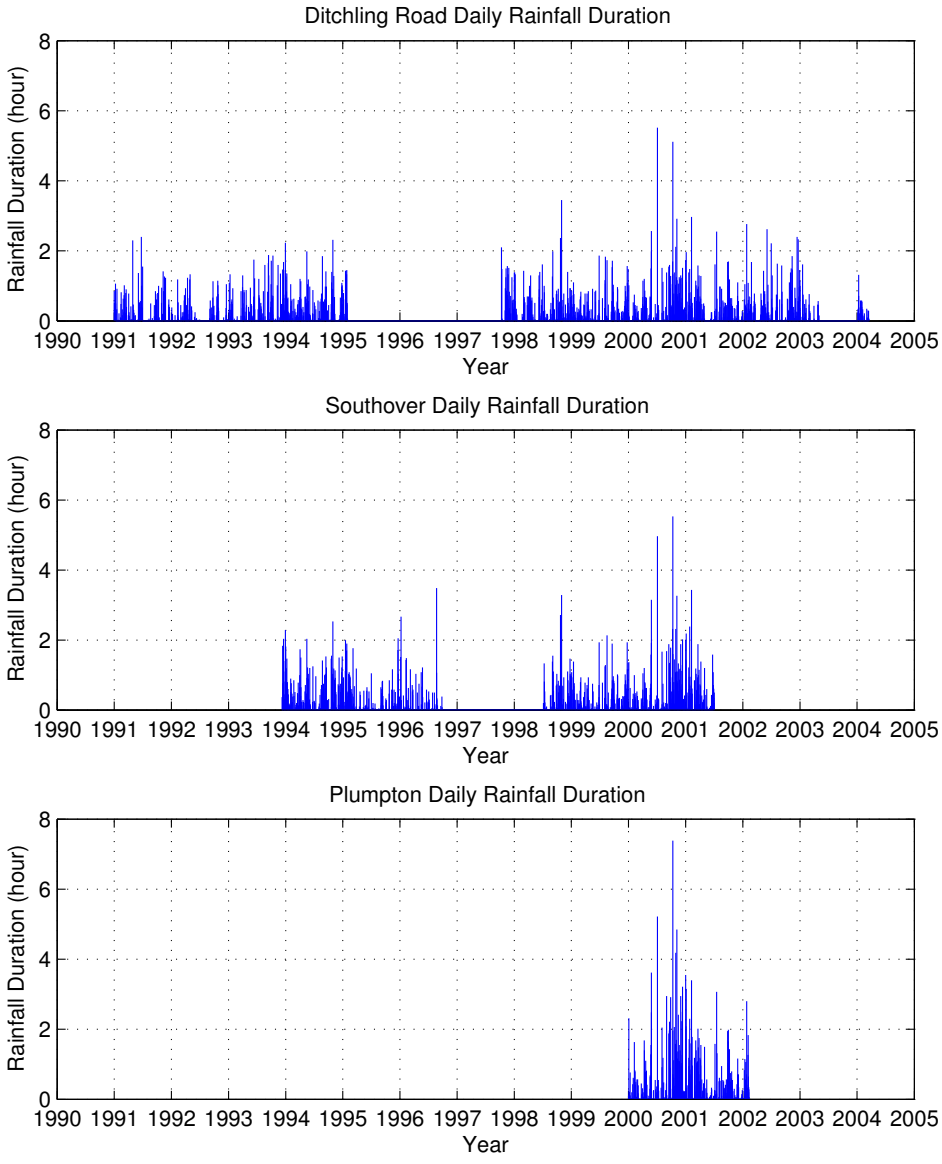


Figure 3.16 Observed daily rainfall duration

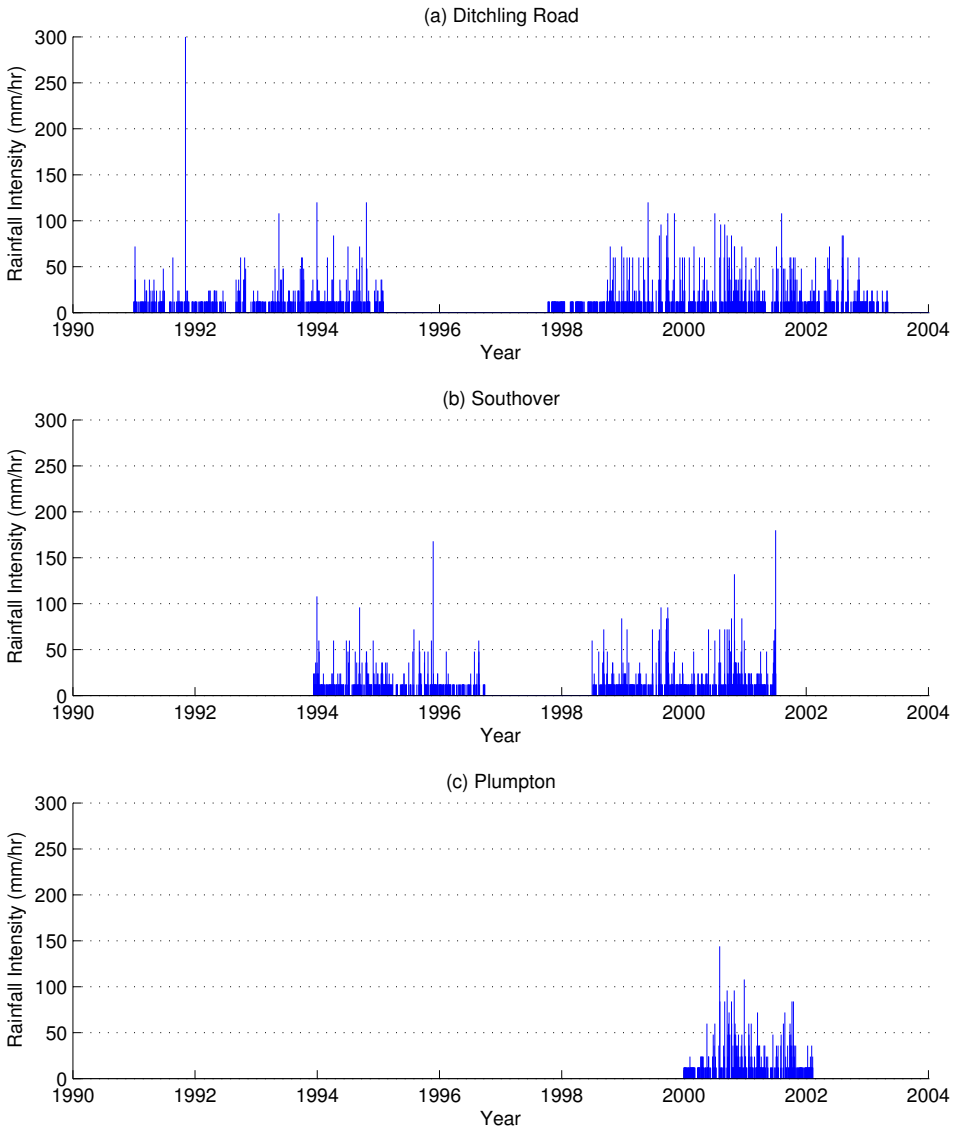


Figure 3.17 Observed daily 1-min peak rainfall intensity.

Rainfall Amount The observed mean monthly rainfall amount is shown in Figure 3.18. All the stations showed the October peak in rainfall amount. Plumpton station showed a large difference of the rainfall amount between October and June (Figure 3.18).

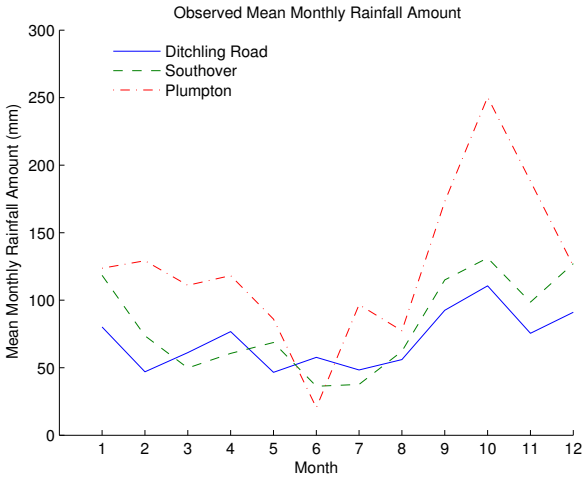


Figure 3.18 Observed mean monthly rainfall amount

Rainfall Duration The mean monthly rainfall duration is shown in Figure 3.19. The mean monthly rainfall duration shows the similar characteristic October peak as the mean monthly rainfall amount.

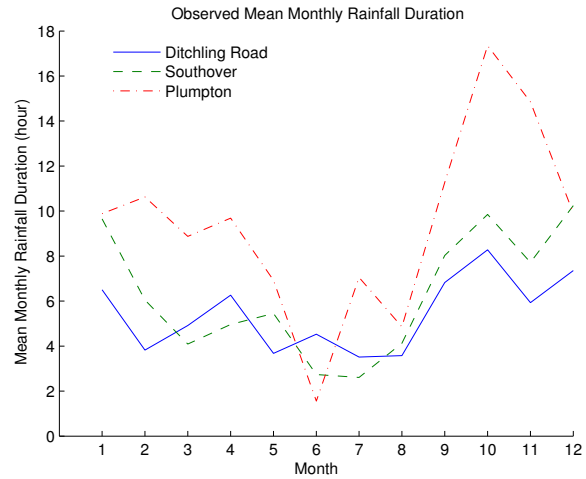


Figure 3.19 Mean monthly rainfall duration

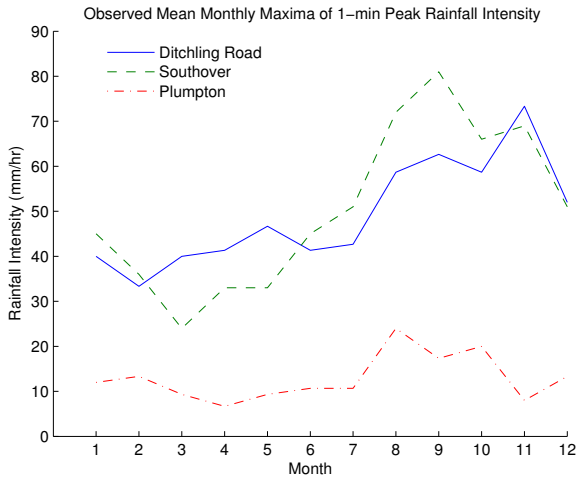


Figure 3.20 Mean monthly maxima of 1-min peak rainfall intensity

Rainfall Intensity The maximum daily 1-min rainfall intensity series for Ditchling Road, Southover and Plumpton are shown in Figure 3.17. The highest 1-min peak intensity reaching at 300 mm/hr was observed on 5 November 1991 at Ditchling Road (Figure 3.17).

The mean monthly maximum 1-min rainfall intensity is shown in Figure 3.20. The highest values were observed in November, September and August at Ditchling Road, at Southover and Plumpton, respectively.

The mean monthly maximum 30-min rainfall intensity is shown in Figure 3.21. The highest values were observed in August, September and August at Ditchling Road, at Southover and Plumpton, respectively.

3.4.6 Discussion

Monthly 0.5° grid rainfall data provide a long-term rainfall trend over a 100 year period. However, this trend is based on monthly mean rainfall amount. Thus, no information on rainfall intensity is given.

Daily station rainfall data have been analysed to find out the trend in various rainfall

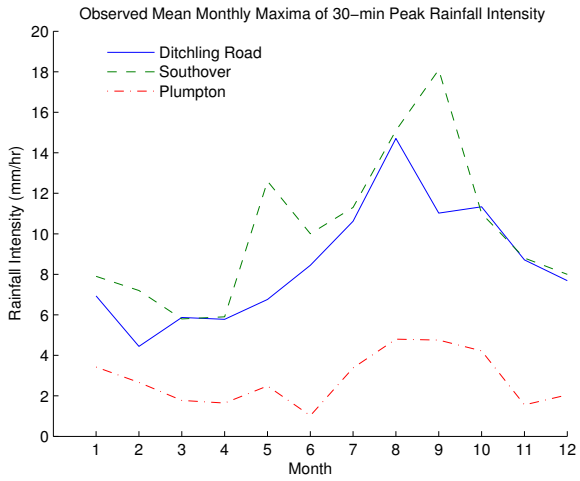


Figure 3.21 Mean monthly maxima of 30-min peak rainfall intensity

characteristics including daily rainfall intensity. These trends are station specific, so that each station may have different trends in rainfall from one to another. The daily intensity trend does provide a trend in rainfall intensity. However, in general, sub-daily data are required to estimate soil erosion using the present process-based models such as ones like WEPP, EUROSEM and RillGrow which are used in this research.

It has been shown that the months of July and March have decreasing trends in rainfall amount, that the annual number of wet days is declining, and that yet the trend in daily rainfall intensity is increasing. It has also shown that there is an increasing trend in the number of wet days with rainfall greater than 10 mm at Falmer Farm and Plumpton stations. No station has shown a significant trend in the annual number of wet days with rainfall greater than 20 mm. This is probably because there are only few records of such event. The station with the longest data duration (FF) show about less than 5%, on average, are rainfall event with ≥20 mm, annually.

Tipping-bucket event data evidently gave greater detailed information about rainfall intensity than the other two data types used here. Tipping-bucket event data provide sufficient information about rainfall features for erosion modelling such as duration

and peak intensity of the rainfall event. The rainfall parameters for soil erosion model simulation conducted in this research are based on the tipping-bucket data shown in Table 3.2. However, these kind of data may not be suitable for trend studies. This is partly due to the fact that they are not easily accessible and not normally stored long-term.

The range of different scaled data gave some clues for future rainfall intensity of the study site. The long-term records—monthly and daily—agree broadly with the latest IPCC report, which suggests more extreme rainfall for the future. However, it is not yet clear how extreme it is going to be.

To determine the rainfall *intensity* trend for future erosion estimation, one should have long term records of sub-daily rainfall records. The most common and easily obtainable long term data are daily data. This may give a hint of future rainfall intensity. However, with daily data alone, it is very difficult to estimate rainfall intensity that is useful enough for soil erosion prediction. The availability of sub-daily rainfall data with a long continuous data period is very limited, so that it is very hard to find such data. With intensive monitoring network growing worldwide, high resolution data (i.e. event data) are becoming more and more available to researchers.

There have been few short term high resolution rainfall data available for this research. With this high resolution data, one may be able to obtain sufficient rainfall intensity information for soil erosion modelling. This, however, is not sufficient for trend estimation. This causes problems in estimating future soil erosion. Simply put, there are not many sub-daily long term data records available for studies like the present research which aims to find trend in rainfall intensity.

Knowing the rainfall intensity trend is important for soil erosion estimation for the future. However, detecting the rainfall intensity trend is very problematic considering the variability of available rainfall data scales. Different temporal scales and spatial scales

can alter the trajectory of the rainfall intensity trend greatly. Also, rainfall data coarser than a daily scale can not give any useful rainfall intensity information for soil erosion estimation as rainfall intensity patterns within a day can not be determined.

Daily rainfall duration can be seen in two ways. One is from the start of the storm to the end of the storm. The other is a net duration, which is a sum of the unit time steps during which the rainfall occurred. The latter concept has been employed for rainfall intensity studies and WEPP (although the reason for this choice is undocumented), despite the former definition being more realistic.

The patterns of mean monthly peak rainfall intensity (e.g. 1-min peak) seem to follow rainfall amount and rainfall duration at the studied stations. This means the more the rain, the longer the duration, so that the higher the intense rainfall intensity, in general. For example, when you get a short burst of high intensity rainfall, the total rainfall amount may be relatively small. However, it still exhibits a high rainfall intensity. High rainfall intensity is closely related with high erodibility. Thus, it is important to look at the details of rainfall intensity details including peak rainfall intensity for soil erosion researches.

When an extreme rainfall event occurs, it may be a rainfall event either with great quantity, with great intensity or with great quantity and intensity together. This categorization is essentially dependant on one item of information, namely time. It is also important to note that as the intensity is time-dependant (the rate of rainfall), changing the time interval for intensity calculation will results in different intensity patterns. This was the case for Ditchling Road—the November peak in 1-min data was replaced by August peak in 30-min (Figure 3.20 and Figure 3.21). Thus, it may be useful to look for trend of monthly rainfall intensity shift. The change of monthly rainfall intensity may affect soil erosion because of the timing of tillage management.

Without the information on how long the event lasted, rainfall intensity can not be calculated. Moreover, even if we do know the start and end time of the event, there is no way we can determine intensity changes during the storm without the data with appropriately fine scales. By knowing the start and end time, only the average intensity over the storm duration will be obtainable. Most erosion models nowadays—so-called process-based models—would not give useful estimates of erosion with average intensity only. They require sub-daily rainfall data.

Evidently, we need to know future WSIV, WSIP and WSP in order to improve erosion prediction. As far as this research is aware, currently RCMs and GCMs rainfall data have not been tested on these characteristics. However, it would not be surprising to find these values predicted by RCM and GCM have high uncertainty levels. Rainfall data should be studied more in detail by looking at these three values and how they are related to erosion processes, so that these values can be better incorporated into erosion models.

It already is difficult to find trend of intensity and 30-min peak intensity using observed data. It will be even more difficult to predict future WSIV, WSIP and WSP using climate model predicted data. Therefore, future scenarios have been built and simulated future erosion with the continuous model (i.e. WEPP).

3.4.7 Conclusion

We know rainfall amounts are going to be change in the future, but what about intensity? Trenberth (2003) calls more researches for this issue.

Despite the various efforts to find meaningful rainfall intensity trend for building future scenarios of rainfall intensity changes, no significant trend can be determined because of the great variability in the high resolution rainfall data. It is necessary to draw out the significant trend from data with sufficient scale that can be used in erosion

modellings.

To achieve the aim of this research, an alternative method has to be sought to obtain future rainfall data with a appropriate data scale and 'changed' rainfall intensity. The process of finding alternative method is discussed in the next chapter (Section 9.2).

This chapter has tried to answer the following research questions:

- What are the main properties of present-day rainfall in the study site?
- Will the future rainfall intensity be different from the present? If so, is it going to increase, decrease or stay the same?

In this chapter, it has been shown that:

1. the month of July and March have decreasing trends in rainfall amount;
2. the annual number of wet days is declining, and;
3. yet the trend in daily rainfall intensity is increasing.

It has also shown that there is an increasing trend in the number of wet days with rainfall greater than 10 mm at Falmer Farm and Plumpton stations although no station has shown a significant trend in the annual number of wet days with rainfall greater than 20 mm.

During investigations of the rainfall trend, the following were recognized:

- To determine the trend in rainfall intensity, the detailed rainfall record is needed.
- Rainfall intensity trend is not the same as rainfall amount trend
- Duration of the data record limits validity of the trend.

- Availability of long-term high-resolution rainfall record is paramount for the investigation into the trend in rainfall intensity.

PART II

Rainfall Intensity and Erosion: Model Descriptions and Responses

Chapter 4

IMPLICATION OF IMPROVED CLIGEN ON RAINFALL AND SOIL EROSION SIMULATIONS

4.1 Introduction

CLIGEN, a weather generator for WEPP, went through extensive modifications while the current research was carried out (Yu, 2000). The modification was done to improve CLIGEN in three aspects. The first is the recalculation of an input parameter, 'MX.5P', which controls rainfall intensity generations of CLIGEN. The second is the correction of the unit conversion error in programming codes of CLIGEN. The third is a subsequent adjustment to shorten the extensive increases of simulated rainfall durations.

These unforeseen changes prompted an investigation of their implications on rainfall generations of CLIGEN and, in turn, soil erosion estimations of WEPP. Before using the improved CLIGEN, it is important to understand how the improved CLIGEN perform

and simulates weather data in comparison to the previous version. Also, how these changes of CLIGEN affect on previous publications needs to be discussed.

Therefore, this chapter investigates effects of the changes of CLIGEN (from version 4.2 to version 5.2) on rainfall data simulations and soil erosion estimations by WEPP. During the investigation process, WEPP is also calibrated and used for the subsequent simulations of this thesis. Some previous publications have been identified later in this chapter in regard to implications of CLIGEN changes.

4.2 Data Preparation and Method for Model Simulation

Firstly, two CLIGEN input files—original and updated (see Appendix B)—were prepared using more recent rainfall data (Table 3.2) obtained from the Ditchling Road site (Figure 3.2). The original CLIGEN input file for Ditchling Road was used in a study by Favis-Mortlock (1998*a*). This file was originally built with help from Arlin Nicks for David Favis-Mortlock in 1992[1]. The newly prepared CLIGEN input file used event data that have been measured since 1991 (Table 3.2). 'MEAN P' (Table 4.2) and 'MX.5P' (Table 4.3) values of CLIGEN inputs were recalculated using the up-to-date event data. Note that the units for these parameters are in inches, not in millimetres. Only these two parameters were updated because rainfall intensity is closely related to these two parameters. The definition of the 'MX.5P' was revised by Yu (2000), so it was recalculated accordingly in this research.

[1]From personal communication with David Favis-Mortlock on 3 July 2001:

> "My problem was that, in 1992, I did not have any measured intensity data for the area. So, as I recall, I used maps in 'NERC (1975) *Flood Studies Report*, Natural Environment Research Council, HMSO, London' to pick out the maximum x-hour precipitation for each month for the South Downs, where x is something like 6 hours. The 1975 NERC report was based on approximately 30 years of data. I then used a chart constructed from empirical relationships in the 1975 NERC publication—Actually, from data given to me by someone in the old Southern Water company, which data was drawn from the 1975 NERC publication—to convert these values into 0.5-hour maxima. I then sent these 0.5-hour max. values to Arlin. From these he calculated time-to-peak values."

Table 4.1 Weather simulation settings with different CLIGEN versions and inputs for Ditchling Road

	Original Input	Updated Input
CLIGEN v4.1	v4.1+original	v4.1+updated
CLIGEN v5.2	v5.2+original	v5.2+updated

Next, continuous daily climate data for 30 years were generated with CLIGEN version 4.1[2] (old) and version 5.2 (new) using these two input files. As a result, four datasets of simulated climate data were generated (Table 4.1). These climate data were compared in terms of rainfall amount, duration and peak intensity.

Table 4.2 Original and Updated MEAN P (inches) for Ditchling Road

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Original	0.19	0.16	0.17	0.16	0.16	0.20	0.19	0.22	0.23	0.27	0.21	0.20
Updated	0.11	0.11	0.18	0.21	0.17	0.15	0.16	0.13	0.24	0.29	0.19	0.29

Table 4.3 Original and Updated MX.5P (in/hr) for Ditchling Road

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Original	0.63	0.59	0.55	0.55	0.55	0.55	0.55	0.67	0.79	0.93	0.87	0.75
Updated	0.27	0.18	0.23	0.23	0.27	0.33	0.42	0.58	0.43	0.45	0.34	0.30

Using WEPP, soil erosion rates for the same thirty-year period were, in turn, estimated for Woodingdean site (Figure 3.3) with each CLIGEN-generated climate dataset. All other input data for the WEPP simulation were acquired from the previous study by Favis-Mortlock (1998*a*). Runoff and soil loss rates were compared. Kolmogorov-Smirnov (K-S) test was used to test the null hypothesis that the two populations are identical. Results of K-S test are presented in the next section.

[2]There is virtually no difference between version 4.1 and 4.2 although version 4.2 was the one Yu (2000) found error in.

4.3 Implication on Rainfall Data Simulation

4.3.1 Rainfall Amount

Generated annual rainfall amounts for 30 years were within the range of the reported annual rainfall amounts (750 and 1000 mm) in the area (Figure 4.1). The annual rainfall amounts generated by two input files were not significantly different (K-S test, $p < 0.05$). Although two versions of CLIGEN resulted in a slight difference in annual rainfall amounts in year 17 (Figure 4.1), the differences between two versions of CLIGEN were not statistically significant (K-S test, $p < 0.05$).

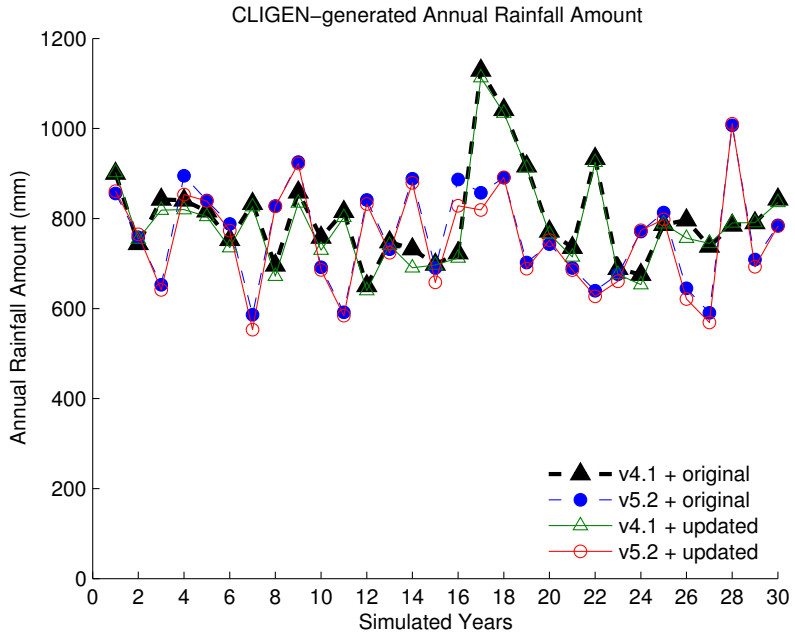


Figure 4.1 Simulated annual rainfall amount using two versions of CLIGEN with original and updated input files.

4.3.2 Rainfall Duration

Contrastingly, simulated annual rainfall durations using two versions of CLIGEN exhibited noticeable differences. Old version of CLIGEN generated identical annual

rainfall durations even though two different input files (original and updated) were used (Figure 4.2). New CLIGEN generated markedly different rainfall durations when the same set of CLIGEN input files were used (Figure 4.2) (K-S test, $p < 0.05$).

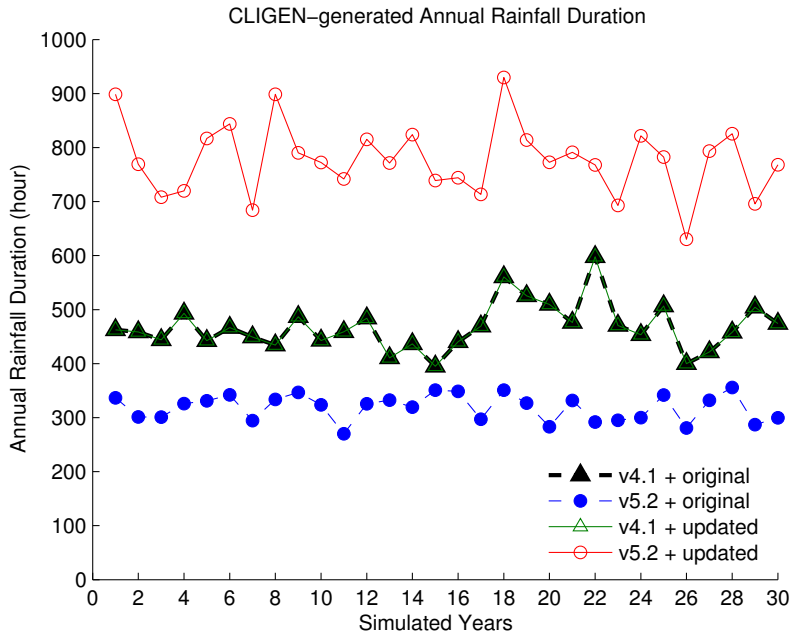


Figure 4.2 Simulated annual rainfall duration using two versions of CLIGEN with original and updated input files.

New CLIGEN with updated input file generated greatly increased rainfall durations, almost 2.5 times longer on average than with original input file. The rainfall duration (v5.2 + updated) was over 1.5 times longer on average in comparison to the rainfall duration generated by old CLIGEN with both original and updated input files. New CLIGEN with original input file generated the shortest annual rainfall durations among the four series. This means that, unlike old version, new version of CLIGEN is sensitive to the change of two CLIGEN input parameters (i.e. MEAN P and MX.5P), particularly to the change of MX.5P. Great differences in rainfall durations mean that rainfall intensities also differ greatly between the simulated rainfall data.

4.3.3 Monthly Maxima of Daily Peak Rainfall Intensity

Next, monthly maxima of daily peak rainfall intensity series generated by CLIGEN were compared in order to examine effects of extreme intensity events. The results are shown in Figure 4.3. Kolmogorov-Smirnov test indicates that old CLIGEN was not sensitive to the changes of input files (See Figure 4.3(a) and 4.3(c), $p < 0.05$). In contrast, using original and updated input files with new CLIGEN resulted in two significantly (K-S test, $p < 0.05$) different distributions of monthly maxima of daily peak rainfall intensity (See Figure 4.3(b) and 4.3(d)). New CLIGEN generated fewer high-peaked rainfall intensity events than the old version (Figure 4.3(a)(c) and 4.3(b)(d)). There were, for example, only nine monthly maxima of daily peak intensity over 100 mm/hr during 30 years of the simulation period when new CLIGEN and updated input file were used (Figure 4.3(d)). The magnitude of the monthly maxima of the daily peak intensity seems to be in a similar range for all four cases although the frequency of such high values may vary depending on versions of CLIGEN and input files.

Mean monthly maxima of daily peak intensity were compared in Figure 4.4. Old CLIGEN with two input files generated generally high mean monthly values through out most of months in comparison to new CLIGEN. The effect of different input files was very small on old CLIGEN for simulating mean monthly maxima of daily peak intensity. Old CLIGEN generated highest mean monthly maxima of daily peak intensity in October and lowest values in June with both input files. In contrast, new CLIGEN generated significantly different mean monthly maxima of daily peak intensity with two input files (K-S test, $p < 0.05$). Much greater mean monthly maxima of daily peak intensity were generated with v5.2 + original than with v5.2 + updated. With original input file, new CLIGEN (v5.2) showed a peak in November and a low in May.

With exception of v5.2 + updated, all three simulations show generally high mean

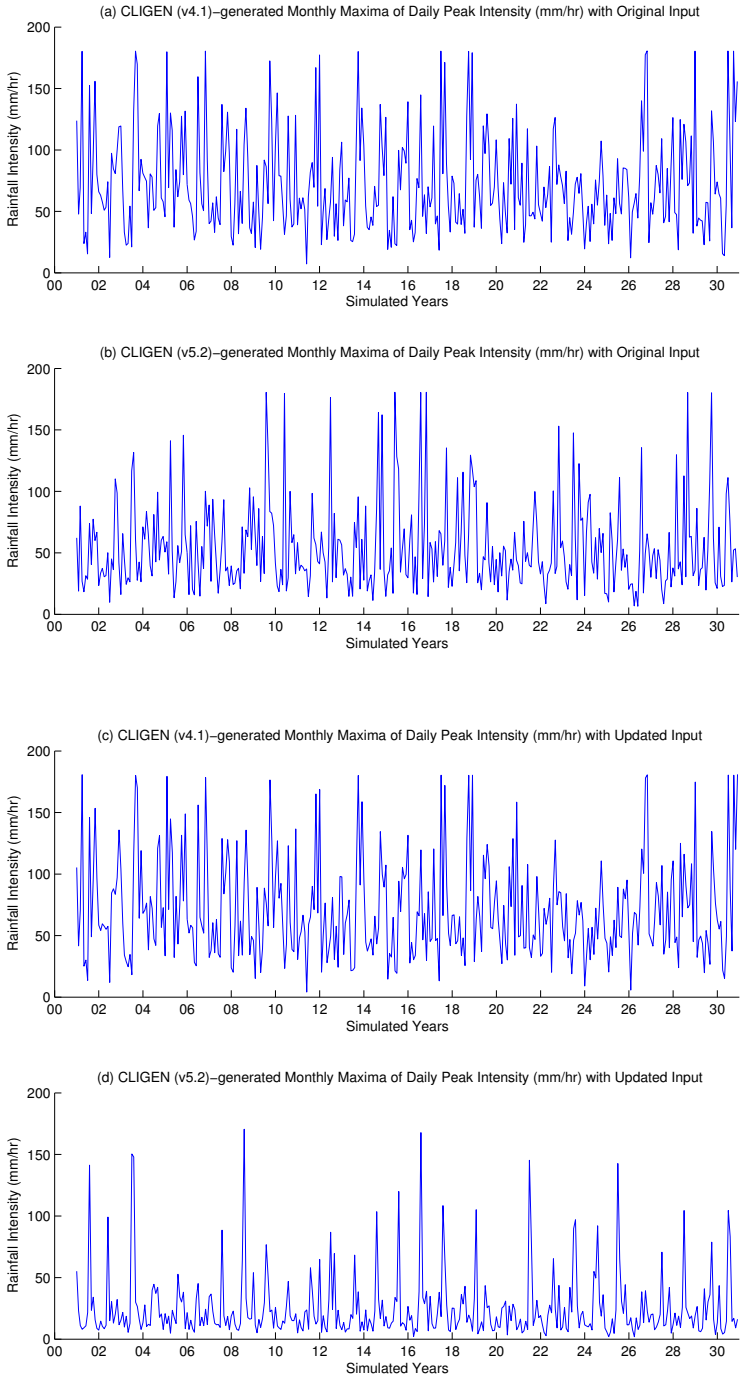


Figure 4.3 Simulated monthly maxima of daily peak rainfall intensity using two versions of CLIGEN with original and updated input files. (a) CLIGEN v4.1 with original input file; (b) CLIGEN v5.2 with original input file; (c) CLIGEN v4.1 with updated input file; (d) CLIGEN v5.2 with updated input file.

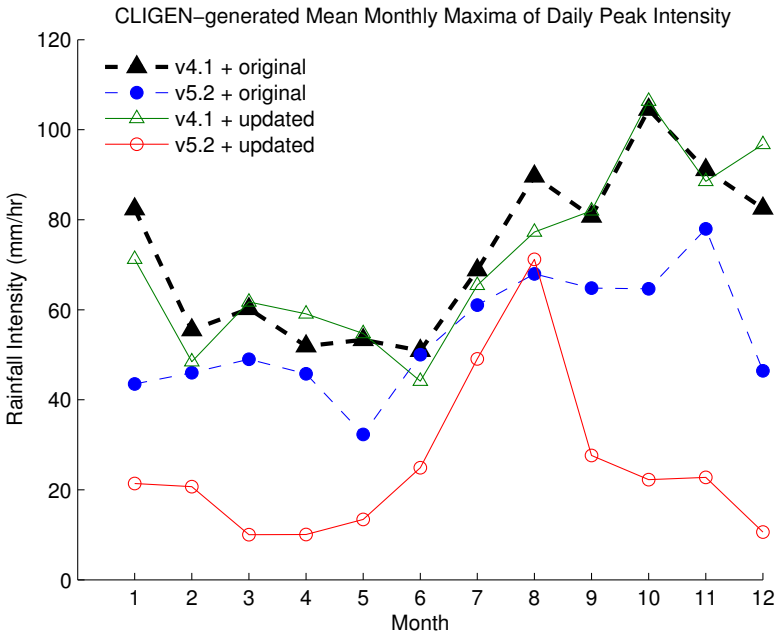


Figure 4.4 CLIGEN-generated mean monthly maxima of daily peak intensity using two versions of CLIGEN with original and updated input files

monthly maxima of daily peak intensity in October and November and low mean monthly maxima of daily peak intensity in April, May and June. When new CLIGEN with updated input file were used for the simulation, the monthly pattern was very different from that of the other three combinations. This combination (v5.2 + updated) showed relatively high mean monthly maxima of daily peak intensity during the summer months (June, July and August) with a distinctively high peak in August (Figure 4.4). Generally low mean monthly maxima of daily peak intensity in the rest of months were simulated with lowest mean monthly maxima of daily peak intensity in March and April (Figure 4.4). With updated input file and new CLIGEN, more high intensity events were simulated in the summer than the autumn or winter in comparison to the other simulation combinations.

4.4 Implication on Runoff and Soil Erosion Simulation

Before starting investigations on effects of improved CLIGEN on WEPP simulations, initial tests of WEPP were carried out with weather generated by new CLIGEN with updated input file. The tests revealed that uncalibrated WEPP overestimates mean soil loss by about 630% in comparison to observed soil losses from the study area (Table 4.5). This erosion rate is considered undesirably high for the study site so that calibrations is considered essential. Thus, WEPP was calibrated by adjusting hydrological and erosional parameter values. The adjusted parameters were shown in Table 3.4. Simulated runoff and soil loss rates using uncalibrated and calibrated WEPP are presented in Table 4.4 and 4.5. There were no measured runoff data available for the site although annual soil loss data for a short period were acquired from Favis-Mortlock (1998*a*).

Table 4.4 Simulated annual average runoff (mm) on hillslopes (D-L) using CLIGEN-generated (v5.2) weather with updated input

	D	E	F	G	H	I	J	K	L	Mean
uncalib.	106.7	105.3	106.5	106.0	106.1	107.1	107.8	108.0	108.8	106.9
recalib.	74.2	72.9	73.9	73.6	73.4	74.3	74.8	75.2	75.9	74.2

Table 4.5 Simulated annual average soil loss (t/ha) on hillslopes (D-L) using CLIGEN-generated (v5.2) weather with updated input

	D	E	F	G	H	I	J	K	L	Mean
uncalibrated	49.4	42.9	76.1	96.5	117.5	111.1	105.3	84.1	79.7	84.7
recalibrated	3.4	3.2	11.1	18.2	23.7	21.3	17.3	9.8	7.9	12.8
measured[a] (m^3/ha)	3.4	7.8	13.7	17.5	21.4	9.6	11.6	11.2	8.1	11.6

[a] over the periods of 1985-1986 (From Favis-Mortlock, 1998*a*)

Why Calibrate? It is paramount to test and calibrate a model before using it in the subsequent investigation of this research. When a erosion model is used for soil loss estimations, it is important to note that the relationship of model inputs and outputs is non-linear (Favis-Mortlock and Boardman, 1995; Jetten *et al.*, 1999). For example, say,

we ran a erosion model with *Input A* and got *Output B* (Figure 4.5). Then, in order to find possible effects of changes ininputs, we may change *Input A* to *Input A*'. When the model was run with *Input A*', the responding model output should be *Output B*' if the model has a linear relationship between inputs and outputs. However, because of the non-linear relationship, the responding output may be rather unknown *Output B*" (Figure 4.5). This means that, unless model inputs and outputs are identified and the model is calibrated against known output values, it may be difficult to measure the extent of changes in model predictions. This is because we may not know where unknown *Output B*" has arrived from. Therefore, it is very unlikely that non-calibrated models will lead to reasonable simulation results.

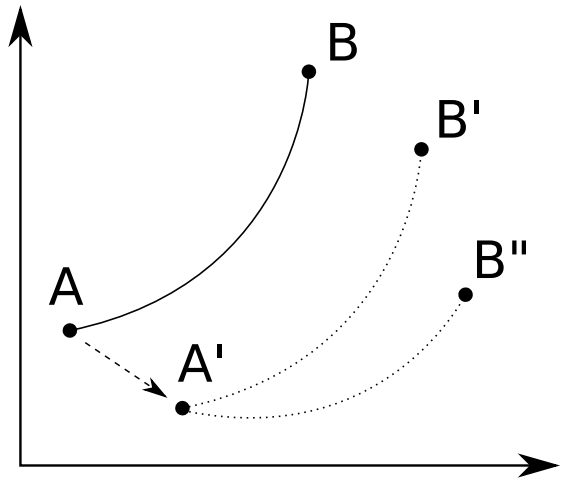


Figure 4.5 A graphical representation of non-linear responses of a erosion model

WEPP simulated annual runoff and soil loss rates using four CLIGEN-generated weather series are shown in Figure 4.6 and Figure 4.7, respectively.

Annual runoff and soil loss rates were not significantly affected by the use of weather datasets that have been generated by old CLIGEN (v4.1) with two input files (original and updated). Annual runoff (Figure 4.6a and Figure 4.6b) and annual soil loss rates (Figure 4.7a and Figure 4.7b) were almost identical between the two configurations (v4.1 + original and v4.1 + updated). Mean annual runoff and soil loss rates estimated using

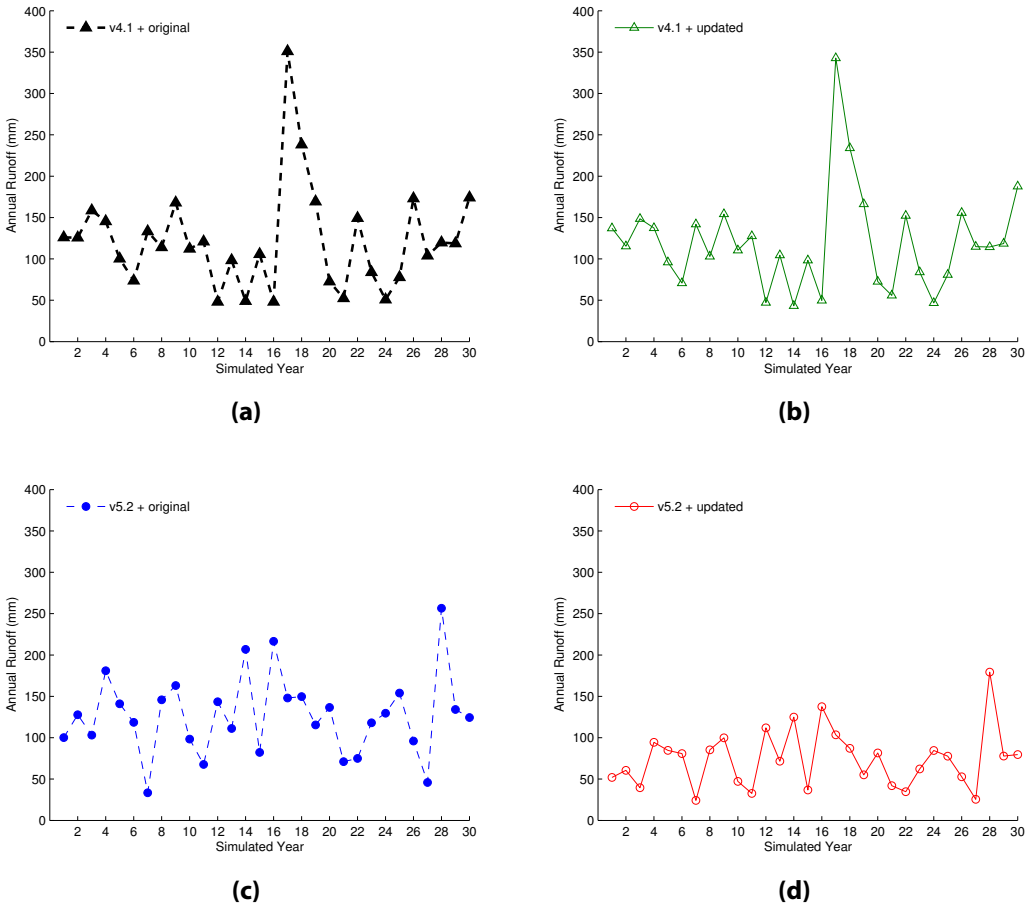


Figure 4.6 Simulated annual runoff for Ditchling Road simulated with (a) old CLIGEN with original input file; (b) old CLIGEN with updated input file; (c) new CLIGEN with original input file; (d) new CLIGEN with updated input file. Note the same Y-axis in plots.

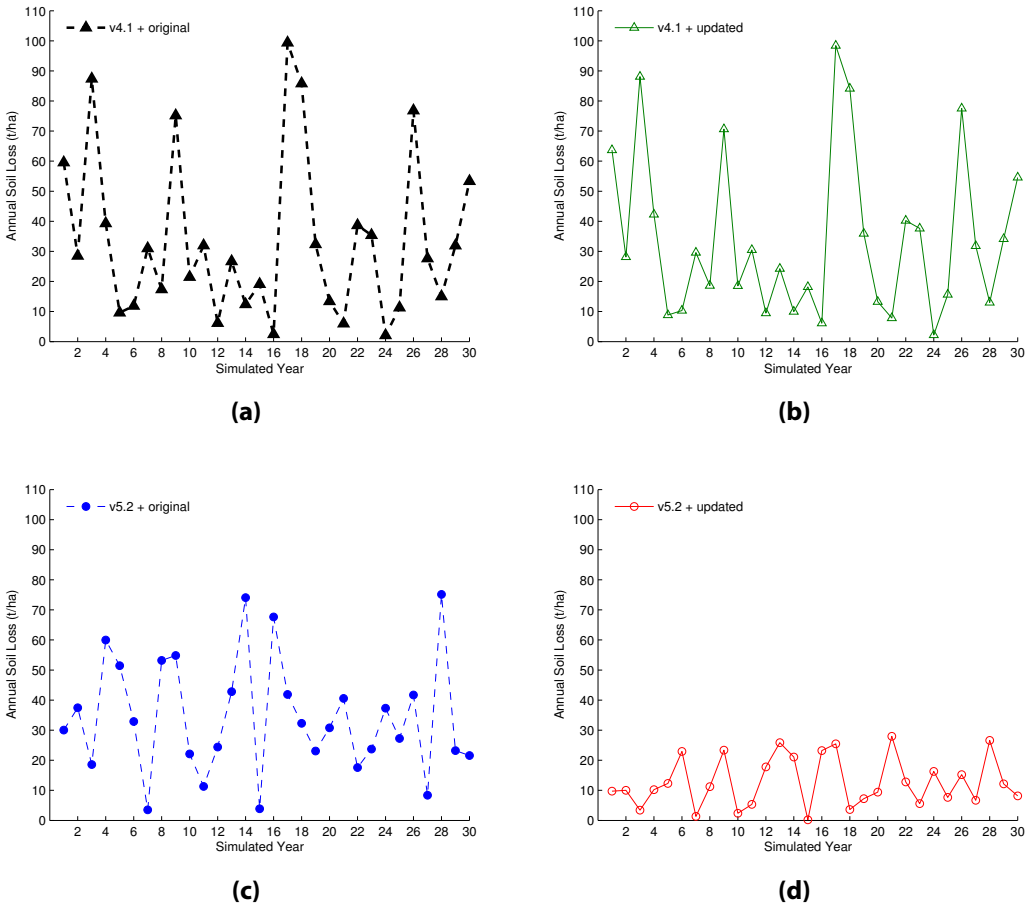


Figure 4.7 Simulated annual soil loss for Ditchling Road simulated with (a) old CLIGEN with original input file; (b) old CLIGEN with updated input file; (c) new CLIGEN with original input file; (d) new CLIGEN with updated input file. Note the same Y-axis in plots.

weather data generated by v4.1 + updated were slightly decreased by 1.4% and increased by 1.5% respectively in comparison to the estimation done by the use of weather data generated with v4.1 + original (Table 4.6).

Table 4.6 WEPP simulated average annual runoff (mm) and soil loss (t/ha) with CLIGEN generated weather with four different configurations.

	CLIGEN v4.1		CLIGEN v5.2	
	original input	updated input	original input	updated input
Runoff	122.1	120.4 (−1.4)	126.5 (+3.6)	74.2 (−39.2)
Soil Loss	33.6	34.1 (+1.5)	34.4 (+2.4)	12.8 (−61.9)

Figures in ( ) represent % differences from CLIGEN v4.1+original input file.
+/− sign indicates an increase/decrease.

When both CLIGENs (v4.1 and v5.2) were run with original input file to generate weather data, subsequent WEPP estimations of average annual runoff and soil loss were not much different between the two versions of CLIGEN. Average annual runoff and soil loss were only increased by 3.6% and 2.4%, respectively. (Table 4.6).

WEPP estimated considerably decreased runoff and soil loss rates when rainfall data generated by new CLIGEN with updated input file were used (Figure 4.6d and Figure 4.7d) in comparison to the other three configurations (Figures 4.6a–c and Figures 4.7a–c). This result is consistent with the result from rainfall simulations. In comparison to mean runoff and soil loss rates estimated using rainfall data generated by old CLIGEN with original input file, the runoff and soil loss rates decreased by about 39% and about 62% respectively when rainfall data generated by new CLIGEN with updated input file were used for WEPP simulations (Table 4.6). The importance of these results are discussed in the following section.

Relative vs Absolute Model Output In this research, both relative (% change) and absolute (t/ha) values were used for model outputs. It may seem more meaningful to use only relative representations (% change) of model outputs than to use absolute values

(t/ha) together with % changes because what this research is interested in is how model estimates change as a result of rainfall intensity changes. However, in order to make a right judgement and to assess estimated values correctly, we need both expressions: relative and absolute. For instance, if a model estimates soil loss of 1000 t/ha from a 1 m×1 m plot after 10 mm/hr rainfall, it would hardly be considered realistic, and the model and its inputs may need to be checked to find a reason for the error. On the other hand, when a model estimates soil loss that changes from, say, 0.00001 t/ha to 0.00002 t/ha, the % change would be 100% despite the fact that this value can be seen as very trivial in the real world. Thus, presenting the model result either only in relative (% change) or absolute (t/ha) value is probably misleading. Therefore, both expressions are used in this research when simulation results are presented. Also, calibrations carried out previously provide robust realistic absolute values.

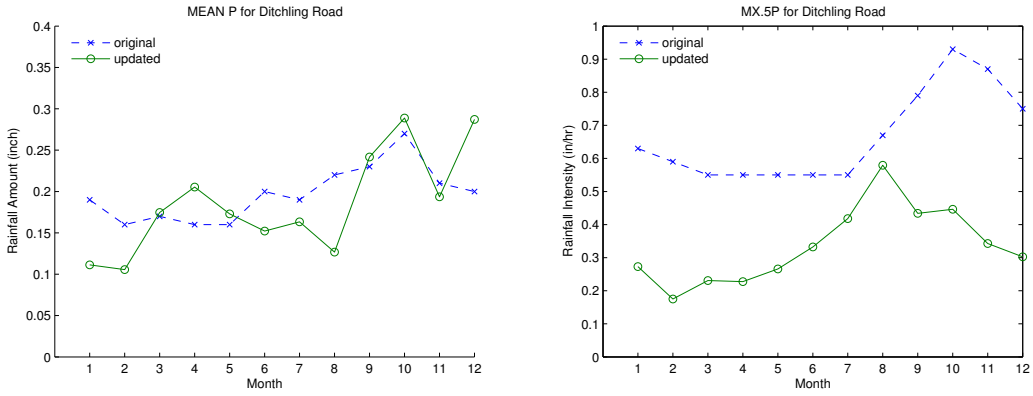
4.5 Discussion

4.5.1 Impact on Rainfall Intensity Generation

Yu (2000) suggests that CLIGEN became sensitive to the change of the rainfall intensity parameter because of the improvement. This investigation confirms this improvement. Rainfall duration generated by new CLIGEN (v5.2) showed a clear signs of the sensitivity to the change of rainfall intensities which is shown in Figures 4.2 and 4.4.

Updated CLIGEN input file has lower MX.5P values than original input file. This difference led to longer rainfall durations generated by new CLIGEN (v5.2) as shown in Figure 4.2. This was expected because of the lower MX.5P values and the similar MEAN P values in updated input file in comparison to the same parameters in original input file (Figure 4.8). With rainfall amount being almost unchanged—only slightly changed, but statistically the same ($p < 0.05$), rainfall duration has to be increased to

satisfy low intensity parameters (Figure 4.8). This, in turn, decreases rainfall intensities generated by new CLIGEN (Figure 4.4, v5.2 + updated).



(a) MEAN P **(b)** MX .5P

Figure 4.8 Mean daily precipitation depth (inch) and mean maximum daily 30-minute rainfall intensity (in/hr) for each month. Note that the units are in inches, not in millimetres, as CLIGEN requires these values in inches.

Old CLIGEN (v4.1) did not show much changes in rainfall intensity even though the rainfall intensity parameter (MX.5P) were updated to the lower values when the input file was prepared. This insensitivity of old CLIGEN (v4.1) is clearly the result of the unit conversion error previously found by Yu (2000). Correcting the errors in the previous version of CLIGEN resulted in the decreased rainfall intensity (Figure 4.4).

One interesting finding is that when original CLIGEN input file was used for both climate simulations with old and new CLIGEN, rainfall durations generated by two CLIGENs were not significantly different so thus resulting intensities. This finding may be explained by the differences in two versions of CLIGEN. New CLIGEN (v5.2), as shown earlier, is much more sensitive to changes in rainfall intensity than old CLIGEN (v4.1), so that, with the CLIGEN input file that has low rainfall intensity (i.e. Updated CLIGEN input), new CLIGEN (v5.2) will simulate rainfall data with much lower rainfall intensity, hence longer rainfall durations. This has been shown previously. What is more interesting is that, in contrast, with CLIGEN input file that has high rainfall intensity (i.e.

Original CLIGEN input), new CLIGEN (v5.2) still simulate climate data with responding rainfall intensity, that is high rainfall intensity, hence short rainfall durations. This is more evident as new CLIGEN (v5.2) generated shorter annual rainfall durations with original input file (Figure 4.2) than old CLIGEN (v4.1) with original (or updated) input file. However, when mean monthly maxima of daily peak intensity were compared as shown in Figure 4.4, new CLIGEN (v5.2) generated lower values for mean monthly maxima of daily peak intensity than old CLIGEN with both input files. Overall, this finding means that the improvement of CLIGEN has less impacts on weather generations for regions where high intensity rainfall events are dominant.

Moreover, new CLIGEN with the updated input file simulated a peak monthly intensity in August (Figure 4.4) that can also be seen in the input file (Figure 4.8b). This means that new CLIGEN generates monthly rainfall intensity that are similar to MX.5P values which are calculated from observed weather data. Old CLIGEN, on the other hand, generated the similar monthly rainfall intensity for both CLIGEN input files. This implies that old CLIGEN does not recognize the intensity differences introduced by the different MX.5P parameters in the input files.

Therefore, it is strongly suggested to use new CLIGEN (v5.2) hereafter. It is also advisable to review previous CLIGEN input files when possible.

4.5.2 Impact on Subsequent WEPP Simulation

Runoff and soil erosion rates estimated by WEPP showed the similar responses as those from the analysis of rainfall generations. This implies that WEPP is sensitive to the changes of climate data which have been used for the simulation.

The two identical climate datasets generated by old CLIGEN (v4.1) with two input files (original and updated) did not affect WEPP estimated annual runoff (Figures 4.6a

and 4.6b) and soil erosion rates (Figures 4.7a and 4.7b). There were slight differences between two settings in terms of average annual runoff and soil loss rates (Table 4.6). The differences were however unrealistic as average annual soil loss rate was increased even though average annual runoff was decreased. This suggests that WEPP may have some issues in estimating runoff and soil loss rates.

The use of two climate datasets generated by new CLIGEN (v5.2) with original and updated input files resulted in significantly different runoff and soil loss rates. WEPP simulated considerably lower annual runoff and soil loss rates when climate data generated by new CLIGEN (v5.2) with updated input file were used than when climate data generated by new CLIGEN (v5.2) with original input file were used. This is because of the increased rainfall duration which have been caused by the decreases in rainfall intensity (Figure 4.2). Considering that simulated rainfall amounts were not much different in both input files of CLIGEN, it is evident that low rainfall intensity is the reason for the low annual runoff and annual soil loss rates estimated by WEPP.

Therefore, the implication of the improvement in CLIGEN is relatively small when CLIGEN was used to simulate climate data for a place where rainfall events with high intensity are dominant. On the other hand, when CLIGEN was used to generate climate data for a place where rainfall events with low intensity are dominant (e.g. South Downs, UK), differences of climate data simulated by old and new CLIGEN would be so great that subsequent WEPP estimations will be greatly affected and erroneous estimations are inevitable.

In the next section, some examples of previously published studies that may have been affected by these CLIGEN improvements are subjectively selected and discussed to highlight the implication of the CLIGEN improvement.

4.5.3 Implication for Previously Published Studies with Old CLIGEN

Published papers that used old CLIGEN, prior to Yu (2000), to generate weather data are theoretically affected by the improvement. The magnitude of effects can vary depending on characteristics of typical rainfall storms in study area as shown in the present research.

Baffaut *et al.* (1996) used old CLIGEN to generate 200 years of climate data for WEPP simulations in order to investigate impacts of CLIGEN parameters on WEPP-predicted average annual soil loss. The study found that only five parameters, that are mean precipitation per event, standard deviation of the precipitation per event, skewness of the precipitation per event, probability of a wet day following a wet day and probability of a wet day following a dry day, influenced the estimated average annual soil loss. However, they found that half hour largest intensity (i.e. MX.5P) and the statistical distribution of the time to peak had less influence on the output. Insensitivity to MX.5P parameter, which Baffaut *et al.* (1996) found, could be the result of the error found in old CLIGEN as Yu (2000) pointed out.

However, it is also possible that the insensitivity to MX.5P was from the characteristic of rainfall storms in the study area. Baffaut *et al.* (1996) considered Indiana, Alabama, Kansas, Colorado, Washington and Virginia, USA. It is suggested that storms with high rainfall intensity is common in the central and eastern United States Ashley *et al.* (2003). This means that the magnitude of effects from CLIGEN improvements could be smaller because the studied area are mostly in the central or eastern US except Washington. As shown in Table 4.6, areas with high rainfall intensity are less influenced by the improvement of CLIGEN.

Therefore, the information and analysis from Baffaut *et al.* (1996) do not provide any conclusive evidence to determine the effect of improved CLIGEN.

Zhang *et al.* (1996) conducted a study to evaluate the overall performance of WEPP in predicting runoff and soil loss under cropped conditions. They also used old CLIGEN to generate the weather parameters in the WEPP climate input files. Although they used CLIGEN, not all weather parameters were generated by CLIGEN. Values for amounts of rainfall, rainfall duration, time to peak intensity and ratio of mean to peak intensity were directly calculated from measured rainfall data for each storm at all the sites they considered. This means that their study may not have been affected by the change of CLIGEN. As this chapter suggested, rainfall duration and intensity are the most affected parameters in WEPP climate inputs.

Baffaut *et al.* (1998) also used old CLIGEN to generate synthetic weather series to analyse frequency distributions of measured daily soil loss values and to determine if the WEPP accurately reproduced statistical distributions of the measured daily erosion series. The sites that they selected for their study were in the eastern USA. They selected the study sites based on length of records, the number of events recorded, and the uniformity of the management practices. This means that the series of weather data generated by old CLIGEN may not have been different statistically compared to measured values because of the high rainfall intensity for their study sites Ashley *et al.* (2003). The paper did not include the result of weather simulations. However, it was indicated that CLIGEN generated data were not statistically different from monitored weather data. Thus, this paper also elaborates that the implication of the change of CLIGEN is small when old CLIGEN was used to generated weather data for areas with high rainfall intensity.

Favis-Mortlock and Guerra (1999) conducted a case study from Brazil to suggest an approach to quantifying the change in risk of serious erosion for venerable areas. Favis-Mortlock and Guerra (1999) used old CLIGEN to generate 100 years of weather data based on current-climate and, then, used three GCMs to perturb 100 years of CLIGEN

generated daily weather data. The area which Favis-Mortlock and Guerra (1999) studied has several monsoon characteristics in addition to the distinct wet and dry seasons (Gan *et al.*, 2004). This means that the area have a large variability in rainfall intensity, which implies that impacts of the change of CLIGEN could be small on the overall result of the paper. However, it could still be possible that rainfall duration and number of extreme events could have been overestimated slightly.

The previously published paper that were discussed here used old CLIGEN for generating weather data. This implies that articles may have been affected by the previous errors of CLIGEN to a certain extend. However, the information included in these articles does not have enough details to determine the extend and the effect of improvements of CLIGEN. Yet, the magnitude of impacts varies depending on how CLIGEN was used and where CLIGEN was used for. In summary, it is evident that previously published papers that uses old CLIGEN to generate weather data for the area, like the central and eastern US or central South America, where high intensity storm is common are not greatly affected, at least, not as much as other places like the southern England where low intensity rainfall is common.

4.6 Conclusion

The improvement of CLIGEN have important implications on generating synthetic climate data and subsequent WEPP simulations of runoff and soil loss rates. Old CLIGEN is not sensitive to changes of rainfall intensity. The previous version generates the similar climate series with original and updated CLIGEN input files that have high and low intensity parameters, respectively. However, new CLIGEN is now sensitive to changes of rainfall intensity which is parametrized as MX.5P. The effect of the improvement of CLIGEN is more (less) significant for the regions where low (high) intensity rainfall events are dominant. All previous articles that used old version of

CLIGEN may have been affected by the errors of old CLIGEN to a certain extend. However, the magnitude of impacts varies depending on how CLIGEN was used and where CLIGEN was used for. It could have been catastrophic to find out the errors of CLIGEN at the later stage of this research because the site where this research is based on is South Downs, UK where impacts of the improvement of CLIGEN are great.

Chapter 5

EFFECT OF TEMPORAL SCALES OF STORM DATA ON EROSION

5.1 Introduction

When modelling soil erosion, finding suitable input data for the simulation is an important part of model-based researches but it is not easy. Ideally, input data need to be measured directly from a study site and parametrized for a model simulation. However, this process requires a great effort and time. It is also frequently affected by geographical and financial situations of research. All these reasons affect how rainfall data are made available in different scales either spatially, temporally or both. Thus, we often end up using what is readily available rather than what is really required by erosion models.

Rainfall intensity is highly variable depending on data scales and where they are measured from (Nyssen *et al.*, 2005). Consequently, using rainfall data that have a undesired data scale for erosion simulations may produce unknown implications that may later lead to inaccurate model outputs. Therefore, this chapter aims to investigate effects of different temporal scales of rainfall data on erosion model simulation processes.

In addition, which data format between CLIGEN and breakpoint data is more suitable for current research was looked at.

The results of this chapter and the subsequent chapters attempts to provide some answers for Research Question 2:

> Assuming that we use a model to predict erosion rates under the future climate which may have different rainfall intensities from the present, what information do we need to make predictions in terms of both climate and process understanding?

5.2 Data Preparation and Method

Definition of Intensity There are two ways of defining average rainfall intensity. One is to calculate kinetic energy of rainfall by measuring size, distribution and velocity of raindrops (van Dijk *et al.*, 2002). The other is to calculate it by dividing total rainfall amount by rainfall duration. The latter is used in this research because erosion models used here employ the latter concept when rainfall data are feed into the model as inputs. Rainfall intensity is expressed as rainfall amount divided by time (e.g. mm/hr) in this research.

Preamble The variations between data points such as breakpoints is termed as Within-Storm Intensity Variation (WSIV) for convenience. This is related to temporal scales of rainfall data as well as types of storms (convective and frontal). In this research, unless specified, a rainfall storm or rainfall event is defined as a daily rainfall. Consequences of this assumption were not covered in this study simply because all models used here assume that a rainfall storm does not last longer than a day. Nevertheless, this research recognises the presence of this issue and the need for further studies on the definition of rainfall storm.

Two storms that occurred on 4 July 2000 and on 11 October 2000 for summer and autumn, respectively, were selected from Plumpton event rainfall data (Table 3.2). The tipping-bucket data for both events were aggregated into 5 different temporal scales—1, 5, 15, 30 and 60 minutes. This was done to simulate different temporal scaled rainfall data. Each temporal scale was treated as if it was the "original" scale for the data with these being the only records available. Two sets of temporally varying summer and autumn storm data were prepared into CLIGEN data format and breakpoint data format for erosion estimations.

CLIGEN rainfall data describe rainfall characteristics with four parameters: total rainfall amount (R, inch), effective rainfall duration (D, minute), normalised time to peak (t_p) and normalised peak intensity (i_p). Effective daily rainfall duration was calculated by summing the number of temporal bins with rainfall on the event day, after removing temporal bins without rainfall. Effects of removing these "gaps" are investigated in the following section, Chapter 6. Normalised time to peak is a relative time of peak intensity after the removal of gaps. Normalised peak intensity is a peak intensity that is relative to average rainfall intensity of the storm. These four parameters were calculated individually for each time-stepped data (Table 5.2), and weather inputs for WEPP were built (Appendix A). Breakpoint data, on the other hand, consist of two parameters: rainfall (accumulated) time and rainfall (accumulated) amounts or intensity. Each dataset was converted into these two parameters, and the number of breakpoints is counted.

Two process-based erosion models, WEPP and EUROSEM, were used at the current stage to simulate runoff and soil loss. WEPP originally requires CLIGEN rainfall data which are stochastically generated using the statistical properties of 15-min rainfall data. CLIGEN data and breakpoint data prepared from rainfall data with 1, 5, 15, 30 and 60-min temporal scale were used to look at the effect of different temporal scale. EUROSEM

was also used since it has been designed to use breakpoint rainfall data. Therefore, it would be a good comparison to WEPP which has been originally designed to use CLIGEN data although breakpoint data could also be used.

As mentioned, EUROSEM uses breakpoint rainfall data only. Thus, unless the EUROSEM code was rewritten, using CLIGEN data directly with EUROSEM is not possible. To use CLIGEN data for EUROSEM simulations, an additional procedure was carried out to make sure that the same rainfall data were used as for WEPP simulations. According to WEPP model document, WEPP disaggregates CLIGEN data into 10 breakpoints using a double exponential equation before calculating erosion related parameters (Flanagan and Nearing, 1995). The disaggregated rainfall data can be found in the WEPP output files. For EUROSEM simulations, CLIGEN data were used as these "WEPP-disaggregated" rainfall data which is in the form of breakpoint data.

Other inputs for EUROSEM were adopted from WEPP outputs as no direct measurements were available to build EUROSEM inputs from scratch. This approach may be problematic for certain modelling studies. However, in this research, it permits a workaround to problems of unavailable factors for EUROSEM simulation. It needs to be noted that the emphasis of this research is not on assessing the performance of models against measured data.

The effect of the temporal scales on rainfall intensity and on runoff and soil loss were examined. For comparison purpose, 15-min data were used as a reference scale when comparisons were done to highlight the effects. Also, this scale is the scale that were used for the CLIGEN development.

5.3 Effects on Rainfall Intensity Information

The highest rainfall amount in Plumpton was 133.8 mm recorded on 11 October 2000. This event at Plumpton on 11 October 2000 was considered responsible for the recent severe soil erosion and flooding in the area (Boardman, 2001; Marsh, 2001; Saunders *et al.*, 2001). The duration of this event was 1208 minutes (i.e. 20 hours and 8 minutes). Average intensity for this rainfall was 6.65 mm/hr. 1-min peak intensity was 84 mm/hr. Typical summer rainfall was recorded on 4 July 2000. Total rainfall amount was 74.8 mm and durations was 808 minutes (about 13.5 hours). Average intensity for this event was 5.5 mm/hr while 1-min peak intensity reached 60 mm/hr. The details of two events are summarised in Table 5.1.

Table 5.1 Details of two rain storms observed in Plumpton

	11 October 2000	4 July 2000
Amount (mm)	133.8	74.8
Total duration (min)	1208	808
Average intensity (mm/hr)	6.7	5.5
Effective duration (min)	460	313
1-min peak intensity (mm/hr)	84	60

WEPP weather input data for two storms were built by obtaining rainfall amount, duration, peak intensity and time to peak. These values are individually calculated for each temporal scaled data. The details of the input parameters are shown in Table 5.2.

For CLIGEN data (Table 5.2), each set of temporally varying rainfall data shows different total rainfall durations depending on what time interval they were aggregated into. Effective rainfall duration increases as the data scale increases. Peak rainfall intensities are also affected by the data scale while total rainfall amounts are the same. This means that only rainfall intensity information is different for each temporal scale. It is also found that the change of temporal scale can shift the temporal location of

Table 5.2 CLIGEN data parameters for two rain storms observed in Plumpton

	11 October 2000				4 July 2000			
	amount (mm)	duration† (hr)	t_p	i_p	amount (mm)	duration† (hr)	t_p	i_p
1-min	133.8	7.4	0.12	4.64	74.8	5.2	0.63	4.20
5-min	133.8	12.8	0.46	5.53	74.8	11.1	0.58	6.41
15-min	133.8	15.5	0.49	2.87	74.8	13.3	0.54	3.69
30-min	133.8	17	0.93	2.69	74.8	14	0.52	2.95
60-min	133.8	18	0.64	2.23	74.8	14	0.54	2.65

† Effective rainfall duration, t_p: Normalised time-to-peak, i_p: Normalised peak intensity

peak intensity (t_p). This may change the shape of storms from, for example, ascending intensity to descending intensity. Changes of the storm shape are further investigated in Chapter 7.

For breakpoint data, the maximum numbers of time intervals per day are 1440, 288, 96, 48 and 24 for 1, 5, 15, 30 and 60-min data, respectively. The rainfall data with different temporal scales show different rainfall intensity information (Figure 5.1 and 5.2). Higher temporal resolution data show higher instantaneous peak rainfall intensities. With 1-min data, for example, a peak rainfall intensity was over 80 mm/hr (Figure 5.2a). In comparison, 60-min data show no peak rainfall intensity higher than 20 mm/hr (Figure 5.2e). This is because rainfall intensity is averaged over the length of each time step. Time to peak rainfall intensity is also different for each temporal scale (Figure 5.1 and 5.2).

5.4 Effects on Simulated Runoff and Soil Loss

The breakpoint data prepared for both October and July events with 1 and 5-min time intervals could not be used for both erosion models because of model limitations. It was found that WEPP and EUROSEM have a limit in the number of breakpoints that they can process. Thus, no runoff and soil loss rates were estimated with 1 and 5-min breakpoint data.

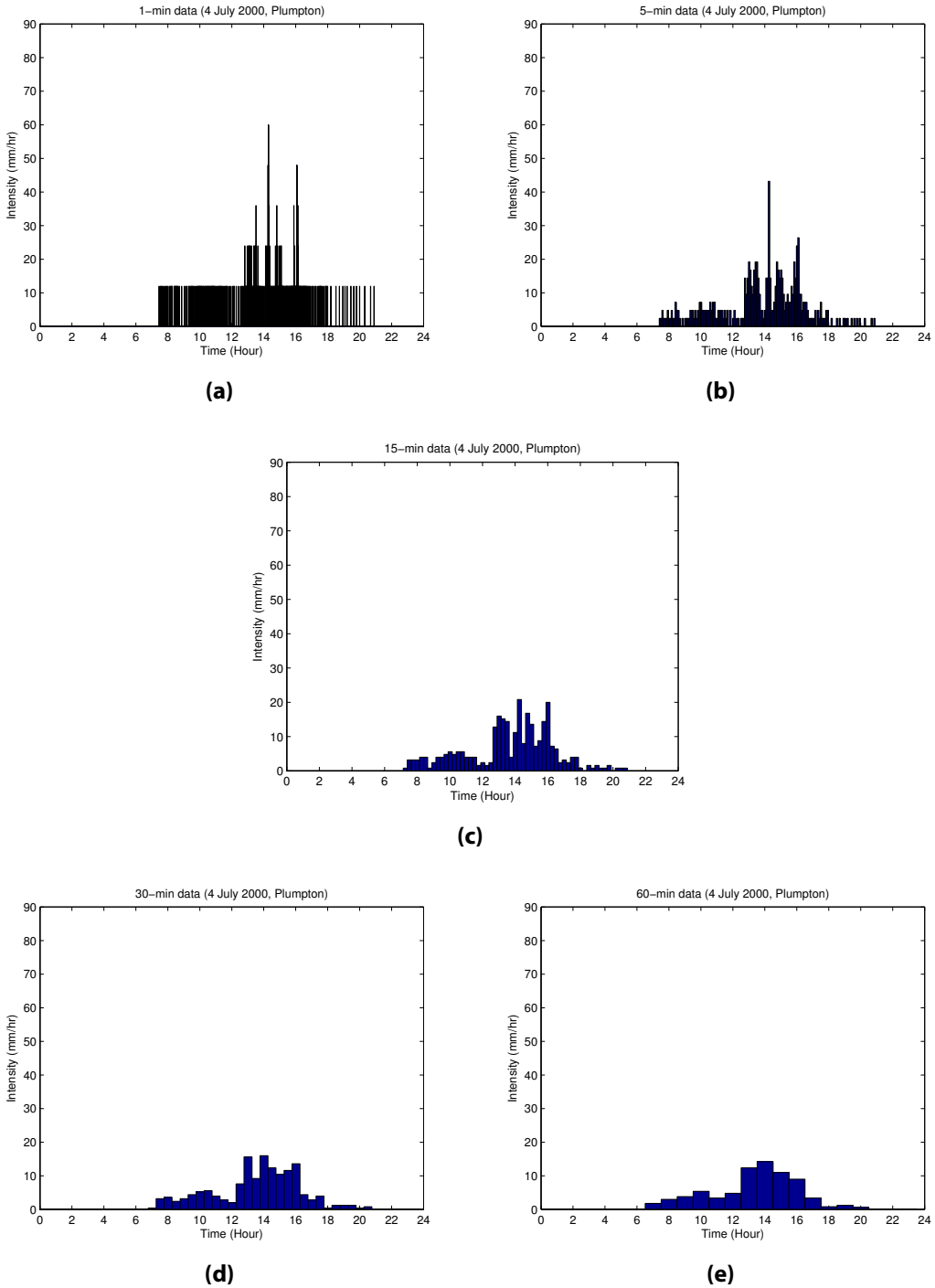


Figure 5.1 Various temporal scales of original breakpoint data for 4 July 2000 storm in Plumpton

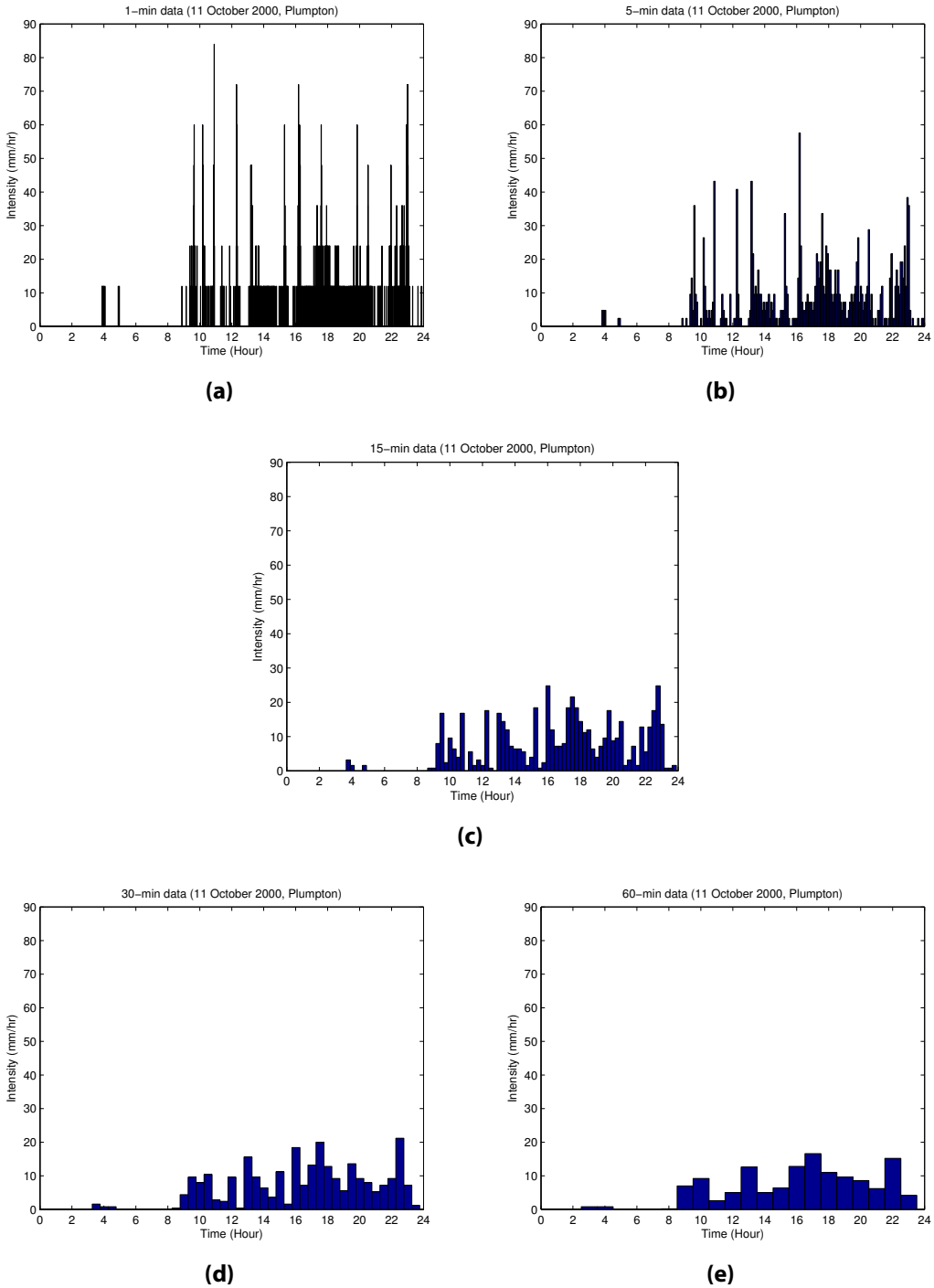


Figure 5.2 Various temporal scales of original breakpoint data for 11 October 2000 storm in Plumpton

5.4.1 Runoff

In overall, both erosion models estimated greater runoff when rainfall data with high temporal scales were used than when low temporal scaled data were used. However, this is only true for CLIGEN data type. For breakpoint data format, the effect of temporal data scales is rather unclear for both models.

Runoff amounts estimated by WEPP for rainfall data with different time scales are shown in Table 5.3 and Figure 5.3(a). WEPP simulation results show that the changes of runoff are greater when simulated with 1 or 5-min CLIGEN data than when simulated with 15-min CLIGEN data. For example, using 1-min data instead of 15-min data for July and October storms resulted in about 45% and 30% increases in runoff amounts, respectively (Table 5.3 and Figure 5.3(a)). Using 60-min data, on the other hand, of the same storms resulted in about 20% and 10% decreases in runoff amounts, respectively (Table 5.3 and Figure 5.3(a)). The effect of temporal scale changes are greater when CLIGEN data for the July event are used than for the October event.

Table 5.3 Effects of different temporal scales of rainfall data on WEPP estimation of runoff (mm)

		Temporal Scale				
Data type	Event	1-min	5-min	15-min	30-min	60-min
CLIGEN	4 Jul 2000	49.7 (+44.5)	44.5 (+29.4)	34.4	29.3 (−14.8)	27.0 (−21.5)
	11 Oct 2000	97.4 (+29.9)	89.4 (+19.2)	75.0	75.0	67.5 (−10.0)
Breakpoint	4 Jul 2000	–	–	30.4	29.8 (−2.0)	29.7 (−2.3)
	11 Oct 2000	–	–	63.9	68.5 (+7.2)	69.9 (+9.4)

Figures in ( ) are the % changes from the result with the 15-min data. +/− indicates a increase or decrease.

When breakpoint data are used, the opposite is observed—the magnitude of the changes are greater for the October event. Also, for the October event, WEPP simulated runoff are greater when simulated with 30 or 60-min breakpoint data than when simulated with 15-min breakpoint data. For the July event, decreases in runoff were

observed when lower temporal resolution data were used for the simulation. Despite this disagreement, changing temporal scales of both types of rainfall data influenced runoff generations of WEPP.

Runoff results generated by EUROSEM for rainfall data with the different time scales are shown in Table 5.4 and Figure 5.4(a). Runoff results from EUROSEM simulations show similar results to those from the WEPP simulation when the CLIGEN data are used. However,the EUROSEM runoff simulation with the breakpoint data show gradual increases for both storms when the coarse scales are used (Figure 5.4(a)).

Table 5.4 Effects of different temporal scales of rainfall data on EUROSEM estimation of runoff (mm)

		Temporal Scale				
Data type	Event	1-min	5-min	15-min	30-min	60-min
CLIGEN	4 Jul 2000	53.3 (+54.1)	42.2 (+22.0)	34.6	31.5 (−9.0)	30.7 (−11.3)
	11 Oct 2000	102.1 (+22.6)	93.6 (+12.4)	83.3	80.1 (−3.8)	75.9 (−8.9)
Breakpoint	4 Jul 2000	–	–	33.2	32.6 (−1.8)	37.0 (+11.5)
	11 Oct 2000	–	–	62.7	69.1 (+10.2)	74.4 (+18.7)

Figures in ( ) are the % changes from the result with the 15-min data. +/− indicates a increase or decrease.

5.4.2 Soil Loss

Soil loss results generated by WEPP for rainfall data with the different time scales are shown in Table 5.5 and Figure 5.3(b). WEPP estimates greater soil loss rates with high temporal scales and lesser soil loss rates with coarse temporal scales in comparison to 15-min data. Soil loss rates is affected more dramatically by the temporal scale changes than the runoff estimations. For example, with the 1-min CLIGEN data for the July event, WEPP estimates soil loss rates almost 300% greater than those with the 15-min CLIGEN data, and an almost 90% decrease in soil loss rate is estimated with the 60-min CLIGEN data for the same event in comparison to the case of 15-min CLIGEN data (Table 5.5 and Figure 5.3(b)). The effect of changes in temporal data scale for the breakpoint data form

show the similar change patterns with the CLIGEN data which is inversely proportional to the temporal scale.

Table 5.5 Effects of different temporal scales of rainfall data on WEPP estimation of soil loss (t/ha)

		Temporal Scale (minutes)				
Data type	Event	1	5	15	30	60
CLIGEN	4 Jul 2000	47.9 (+283.2)	37.1 (+196.8)	12.5	3.5 (−72.0)	1.6 (−87.2)
	11 Oct 2000	101.6 (+163.2)	86.3 (+123.6)	38.6	29.1 (−24.6)	13.0 (−66.3)
Breakpoint	4 Jul 2000	–	–	17.0	11.4 (−32.9)	3.0 (−82.4)
	11 Oct 2000	–	–	37.7	45.0 (+19.4)	16.9 (−55.2)

Figures in ( ) are the % changes from the result with the 15-min data. +/− indicates a increase or decrease.

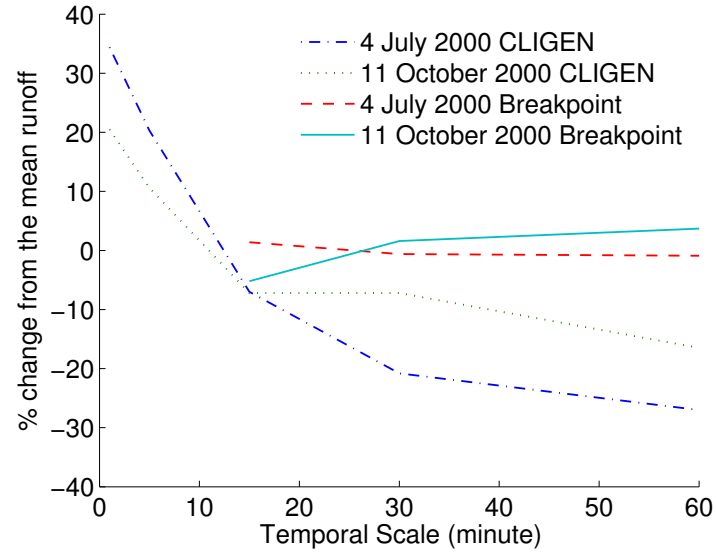
Soil loss rates generated by EUROSEM for rainfall data with the different time scales are shown in Table 5.6 and Figure 5.4(b). The results of soil loss rate simulations using EUROSEM show the reversed effect of the changes in temporal scale on soil loss rates from the effect shown from the WEPP simulation. With an exception of 1-min CLIGEN data, using the coarser temporal scale leads to the greater soil loss rates for all four cases (Table 5.6 and Figure 5.4(b)). The effect of changes in temporal data scales of breakpoint data on soil loss rates is however consistent with the effect of temporal scale changes on runoff simulated by EUROSEM.

Table 5.6 Effects of different temporal scales of rainfall data on EUROSEM estimation of soil loss (t/ha)

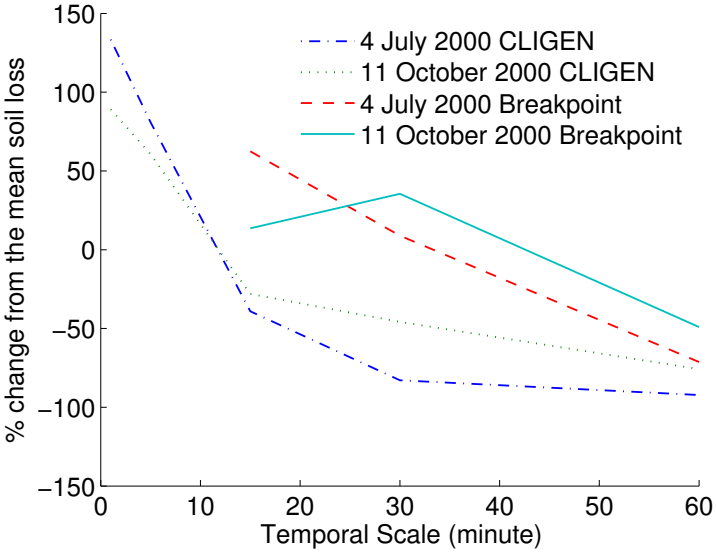
		Temporal Scale (minutes)				
Data type	Event	1	5	15	30	60
CLIGEN	4 Jul 2000	13.0 (+26.2)	10.0 (−2.9)	10.3	10.7 (+3.9)	10.9 (+5.8)
	11 Oct 2000	24.7 (+5.6)	21.5 (−8.1)	23.4	23.8 (+1.7)	25.4 (+8.6)
Breakpoint	4 Jul 2000	–	–	10.0	10.2 (+2.0)	12.0 (+20.0)
	11 Oct 2000	–	–	19.4	21.9 (+12.9)	23.3 (+20.1)

Figures in ( ) are the % changes from the result with the 15-min data. +/− indicates a increase or decrease.

The changes (%) of runoff and soil loss simulated by WEPP and EUROSEM are illustrated in Figures 5.3 and 5.4.

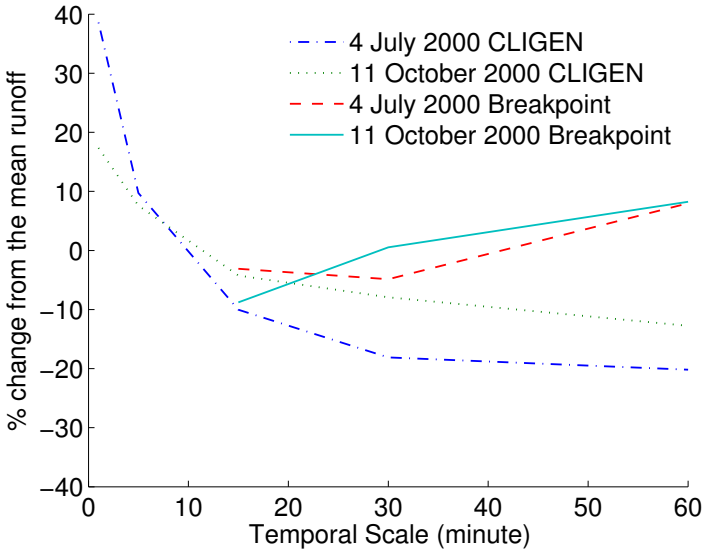


(a) Changes in Runoff

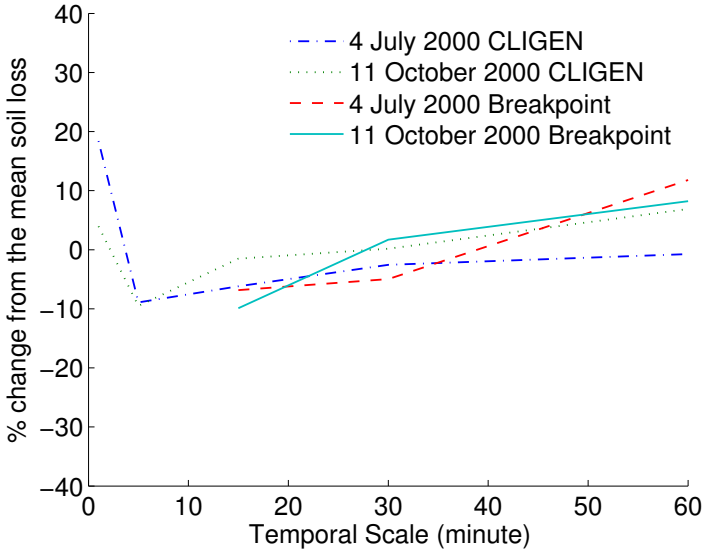


(b) Changes in Soil Loss

Figure 5.3 The changes of WEPP simulated runoff and soil loss from average runoff and soil loss. Note the scale of y-axis in (b) Changes in Soil Loss.



(a) Changes in Runoff



(b) Changes in Soil Loss

Figure 5.4 The changes of EUROSEM simulated runoff and soil loss from average runoff and soil loss

Changes of temporal scales of CLIGEN rainfall data are inversely proportional to WEPP simulated runoff and erosion rates. In comparison to 15-min data, CLIGEN data with higher temporal resolution resulted in greater WEPP simulated runoff and erosion rate than CLIGEN data with lower temporal resolution data. When rainfall data are in breakpoint data forms, temporal data scales have a varying effects on WEPP simulated runoff and erosion rate which do not show clear relationships.

EUROSEM simulated runoff and erosion rate show rather different results from WEPP simulations. Temporal data scales do have effects on runoff and erosion rate simulation by EUROSEM as seen in Table 5.4 and 5.6 and Figure 5.4. However, the result is quite the opposite from WEPP simulations. Breakpoint data with lower temporal resolution resulted in moderate increases of both runoff and erosion rates by EUROSEM. In contrast, CLIGEN data resulted in decreasing runoff and increasing soil loss rates as temporal data scales increase. This result is rather odd because decreasing runoff normally accompanied by decreasing soil erosion rate. Also, 5-min CLIGEN data is the only temporal scale that show decreased soil loss compared to soil loss generated with 15-min CLIGEN data.

Between 1-min data and 60-min data, erosion rate was almost 8-30 times greater when simulated with 1-min data than with 60-min data. This clearly is problematic.

5.5 Discussion

Although WEPP documents states that 15-min data are to be used, the effect of other temporal scales have been explored since 15-min data are not always available for the erosion modelling studies. The results are compared in terms of the rates of changes (%) to highlight the relative effects of the changes only.

Breakpoint data that are prepared for both July and October events with 1 and 5-min

data could not be used for both models—WEPP and EUROSEM. This is because WEPP limits the number of maximum breakpoint to 50 points per day according to the model document (Flanagan and Nearing, 1995). This means that, for a rainfall event that last for a whole day, 30-min data is the highest resolution we can use for WEPP simulations because there are 48 (24/0.5) intervals per day. This prohibits the use of breakpoint data with temporal resolution higher than 30-min in theory. In practice, any temporal scale could be used as long as the total number of breakpoints does not exceed 50 points. Testing with the most up-to-date WEPP revealed that up to 100 breakpoints may be used without a problem. However, when more than 100 breakpoints were used, WEPP does not recognise the start and end of a rainfall event correctly, and re-aggregates the rainfall with multiple starting times (i.e. 0 minute point). The maximum number of breakpoints should be increased to at least 1440 points or more to enable the use of 1-min data or higher temporal data. EUROSEM have the same limitation which prevent from using more than 100 breakpoints. Also, total 1000 breakpoints for simulations with multiple rainfall gauges. Clearly both models need to increase their dimension of breakpoint data array to meet the need.

Rainfall parameters in the CLIGEN input file are originally calculated from 15-min (breakpoint) data. CLIGEN then uses this statistical information to simulate continuous long-term daily rainfall data which has similar statistical characteristics as the observed data in the form of four unique parameters (rainfall amount, rainfall duration, normalised peak intensity and normalised time to peak). These four parameters then were used by WEPP to disaggregate the daily rainfall data into ten breakpoint data using a double exponential function. This procedure is, however, highly inefficient in retaining original rainfall intensity information, particularly for the event with a long duration and low intensity which is similar to the event occured on 11 October 2000. The rainfall information can be distorted or lost during these data "conversion" processes. An

obvious reason why WEPP-CLIGEN use such method seems to be because of the ease of use and data storage for long-term records. This method—statistically summarising historical climate data and maintaining it—is a very efficient way of storing a large amount of rainfall data. One file (i.e. CLIGEN input file) per weather station requires much less space than tipping-bucket data for, say, 10 to 20 years. This however does have a couple of disadvantages:

1. The concept of CLIGEN data is only suitable for convective storms which do not have many intermittent rainfall phases (no-rain periods) during rainfall.
2. For WEPP to disaggregate CLIGEN data realistically using a double exponent function, each storm should have one distinctive high rainfall peak. Such storms are not typical of many parts of the world, and may be seasonally dependant.

It is, however, evident that CLIGEN data type make it easier to deal with vast amounts of data. It also requires considerably less space to store such data. Also, CLIGEN data are very good to use with WEPP as it is designed specifically for such use.

The intensity information of rainfall data is heavily dependant on how they are aggregated. When rainfall data such as tipping-bucket data are aggregated into certain time steps, they are usually stored in a digitized data format. It means the averaged rainfall intensity is dependant on the start time as well as time-steps which is temporal scales. Time-steps and start time are important as the rainfall intensity is averaged over the given time-steps and start point when they are archived. This method, however, unintentionally discards rainfall intensity information by averaging rainfall peaks over the given time step.

The effect of discarding rainfall intensity information has been clearly shown when both events—i.e. rain storms on 4 July 2000 and 11 October 2000—are aggregated into varying time steps. Distinctive high intensity peaks in 1-min data (Figures 5.1a and 5.2a)

was no more visible as intensity was averaged out over the longer timestep data (See Figures 5.1 and 5.2).

Two effects can be noted when the temporal scale changes. One is the effect from the lowering of the actual instantaneous peak intensity and average intensity of the storms. The other is the effect from the location of the peak intensity changes during each storm.

Lowering the average intensity means a reduced average power of erodibility of the rain. Lowering the peak intensity means a reduced instantaneous peak power of erodibility of the the rain. These changes may be a significant reason for the underestimation of the runoff and soil loss. Shifting the location of the peak rainfall intensity means changed rainfall shapes which may be closely related to the timing of the runoff generations. All these changes will occur together when the temporal scale of rainfall data is altered. Thus, what we observed in this study may well be the end product from compound effects of these two changes.

The instantaneous rainfall peak intensity may hold key answers to the processes of dispersion of soil particles. It is known that intense rainfall may exceed the soil infiltration rate faster, so that runoff may occur in a shorter time after the start of the rainfall event compared with low intense rainfall. Wainwright and Parsons (2002) carried out numerical experiments to test if temporal variability of rainfall intensity during a storm can cause the decrease in runoff coefficients with increasing slop length. They found that variability of temporal scale in rainfall is a significant factor in controlling the scale-dependency of runoff coefficients. Also, overland-flow models which use mean rainfall intensities may notably under-predict the runoff.

High rainfall intensity is closely related to high rainfall kinetic energy, which controls runoff generation and soil loss. Yet the way of archiving and aggregating long term rainfall data may miss out important rainfall intensity details as shown in this chapter.

Boardman and Spivey (1987) also pointed out that short period high intensities probably important for soil erosion processes.

Short duration rainfall intensities are affected by a large uncertainty, especially when they are produced during extreme convective rainfall events (Garcia-Bartual and Schneider, 2001). In the study by Garcia-Bartual and Schneider (2001), 408 rainfall events have been statistically analysed for the period 1925-1992 in Alicante (Spain). Maximum intensities for durations ranging from 2 minutes up to 240 minutes were extracted from the series (Garcia-Bartual and Schneider, 2001). Considerable differences are found in the behaviour of the empirical functions for short durations ($t < 10$ minutes) (Garcia-Bartual and Schneider, 2001). The energy of individual storms could only be predicted with limited accuracy because of natural variations in rainfall characteristics (van Dijk *et al.*, 2002).

For future soil erosion studies, one needs to know about future rainfall intensity. But without high resolution rainfall data, one may predict future soil erosion with a large error as shown by this investigation. Even with 15-min data it is possible to get as much as about 3 times less soil erosion estimation compared to 1-min data. This may pose a problem when using large scaled GCM or RCM rainfall data directly for soil erosion. It is relatively difficult to predict rainfall intensity changes with good reliability even with a climate model.

High temporal resolution data are needed in order to describe the temporal variation of rainfall intensities realistically. High temporal resolution data captures in great detail rainfall intensity patterns including instant high intensity peaks. However, such high resolution data are very rarely available. As Allott *et al.* (2002) pointed out, high-resolution data permit a more detailed assessment of the storm structure and evolution of localised intense storms, but storms are rarely monitored by sub-hourly recording rain gauges. Even if storms are recorded by a sub-hour scale, often the records are converted

into hourly or daily for archiving. Thus, a little is ever known about the storm structure and evolution. In many case, therefore, only hourly or daily data are available. Even with hourly (or more generally daily data), the actual rainfall intensity details can not be derived (Figure 5.2) although this information about intensity may be particularly responsible for the runoff and soil loss estimation using erosion models.

Therefore, it is clear that we need to use breakpoint rainfall data with high resolution in order to keep the detail of rainfall intensity as well as maintaining original characteristics of rainfall for erosion simulations. However, high resolution breakpoint data will lead to erroneous simulation results because of the model limitation (i.e. the maximum number of breakpoints) as discussed previously. 1-min and 5-min data cannot be used. Also, the temporal scale of hourly (60-min) data is too long to provide detailed information of rainfall intensity. Now we have left with two choices: 15-min and 30-min data. Without a doubt, 15-min data were chosen because they have greater details of rainfall intensity than 30-min data. Also, both WEPP and EUROSEM can easily used 15-min breakpoint data. It is however important to note that erosion models should be able to take high resolution data such as 1-min breakpoint data and work reasonably well for testing and estimations of erosion.

5.6 Conclusion

Higher resolution dose not always give a better simulation result. Equally low resolution data dose not mean worse simulation results. It can be a problem however when we do not have high resolution data but only low resolution (60-min) data because we will never know what the intensity was like during those 60-min. Also, with no knowledge of the intensity information, simulation results can be anywhere between 8 to 30 times different from "original results". This figure is so great that it might mean from almost no erosion to disastrous events.

In this chapter, the following was found:

- Temporal scales of rainfall data are closely related to the results of runoff and soil loss modelling
- High resolution CLIGEN data generally yield more runoff and soil loss
- Temporal scales of rainfall data affect estimations of soil loss more than runoff
- Effects of the temporal data scale is greater for the summer rainfall event (event on 4 July 2000)
- For the purpose of soil erosion simulation, 15-min breakpoint rainfall data are chosen
- It may be suggested to use breakpoint data for the further simulations in this research

It is also recognised that different ways of expressing rainfall intensity have the tenancy of desirability for erosion modelling. This is summarised in Table 5.7.

Table 5.7 Desirability of different ways of expressing rainfall intensity

Similarity to Reality	Desirability	Method of Rainfall Data Representation
Dissimilar	Most	Amount, Duration, Time-to-Peak & Peak Intensity
↑	↑	Breakpoint Data without 'no rainfall periods'
↓	↓	Breakpoint Data with 'no rainfall periods'
Similar	Least	Tipping Bucket Data

Even though breakpoint data hold more information and are closer to real rainfall than CLIGEN data, it still has some problems. The temporal scale of breakpoint data limits their closeness to real rainfall since rainfall intensity is averaged between starting and ending time of breakpoints.

This chapter is followed by a further research question: '*What is the consequence of removing the no-rain periods within a storm in order to estimate CLIGEN data?*'. The suggested test raises an issue about the no-rain periods that are removed during CLIGEN data preparation which, in turn, may lead to a loss of rainfall intensity information. More worryingly distorting rainfall intensity information and feeding this wrong information into soil erosion models could occur. Thus, only one storm that has few recognizable intermittent no-rain periods within the storm duration is subjectively selected and tested in the next chapter.

Chapter 6

EFFECT OF CONTINUOUS AND DISCONTINUOUS STORM

6.1 Introduction

This chapter investigates the effect of no-rain periods within a storm that is termed as WSP (Within-Storm Pause) on soil erosion estimations. Continuous and discontinuous storms are distinguished by the existence of WSPs within the storm duration.

6.2 Simulation Data and Methods

Three process-based models—WEPP, EUROSEM and RillGrow—were used for runoff and soil loss simulations. Three erosion models were used to highlight the effect of WSP on erosion estimations. Although the outputs from three erosion models could give three very different results—this actually was the case, employing all three models will give a stronger argument that the removal of WSPs does (or does not) have an impact on runoff and soil loss simulations. The main aim of this investigation is to find out

whether WSPs influence runoff and soil loss generations. The more important question is, however, how WSPs influence runoff and soil erosion. This is more difficult to answer even when a single erosion model was used.

Event rainfall recorded on 11 October 2000 in Southover (Table 3.2) was subjectively selected. This event includes a number of WSPs in the total storm duration. The total rainfall amount is 89.9 mm. This event was considered to be responsible for the severe flood incidents in the study region (Boardman, 2001).

As CLIGEN data removes WSPs by its design specification, only breakpoint data type, which retains WSPs, was used in this chapter. Breakpoint event rainfall data with 15-min timestep were used. The reason for the selection of 15-min time scale have been discussed in Chapter 5. Hyetographs of the original October event and the modified October event after removing WSPs are shown in Figure 6.1. The rainfall intensities for each 15-min interval are unchanged (Figure 6.1). WEPP and EUROSEM were used to simulate runoff and soil loss using these data. Total duration of the data with WSPs was 1230 minutes and 885 minutes without WSPs.

Another set of continuous and discontinuous rainfall data were prepared for RillGrow runs. As RillGrow simulates runoff and soil loss in great detail temporally and spatially, rainfall with a relatively short duration and a pulse of constant high intensity peaks were intentionally prepared (Figure 6.2).

Runoff and soil loss rates were simulated with WEPP, EUROSEM and RillGrow using the prepared rainfall data.

6.3 Simulation Results

WEPP estimated runoff amounts for continuous and discontinuous rainfall are shown in Table 6.1. With continuous rainfall, WEPP generated more runoff than with

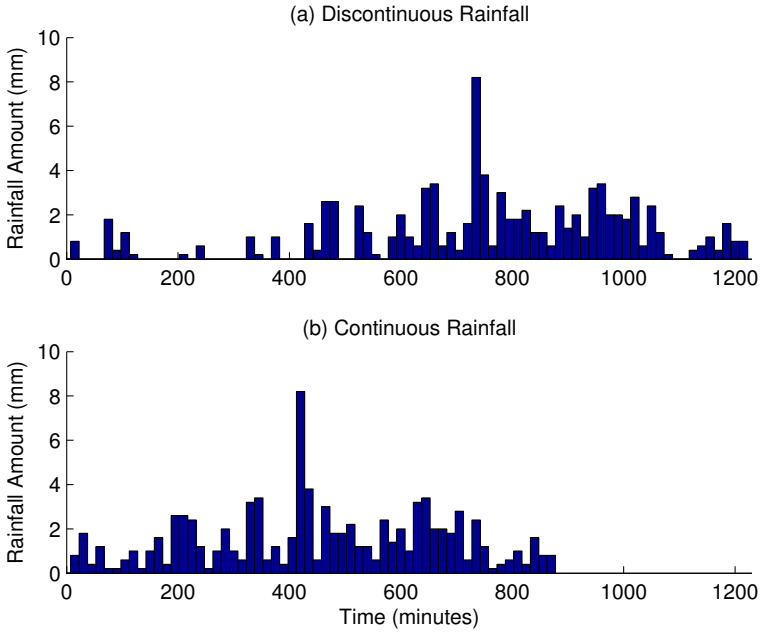


Figure 6.1 15-min rainfall data used for the investigations of effects of continuous and discontinuous rainfall on soil erosion. (a) original 11 October 2000 event ;(b) modified 11 October 2000 event after removing WSPs

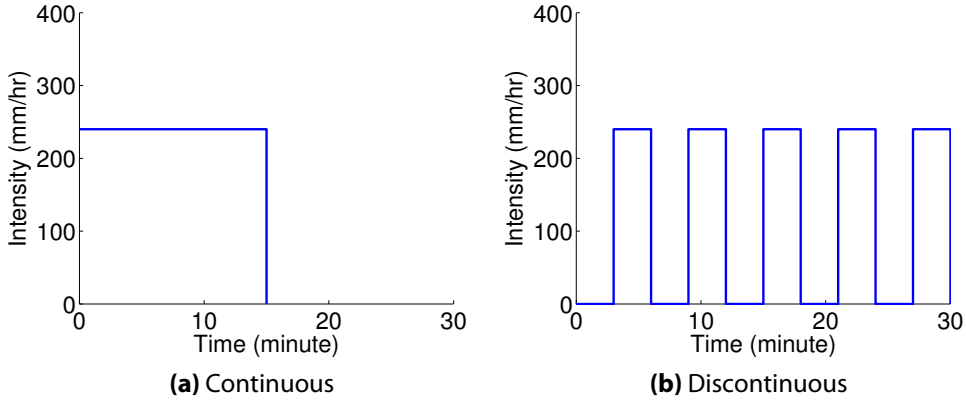


Figure 6.2 Continuous and Discontinuous rainfall for RillGrow simulations. Both storms have the same total rainfall amount of 65.5 mm. Rainfall durations for continuous (a) and discontinuous (b) rainfall are 15 minutes and 30 minutes, respectively.

discontinuous rainfall. However, WEPP estimated less soil loss with continuous rainfall than with discontinuous rainfall. The soil loss rate increases 4.6 percent with a discontinuous storm in comparison to the soil loss rate which is estimated by WEPP with a continuous storm.

Table 6.1 WEPP estimated runoff and soil loss with continuous and discontinuous rainfall for each hillslope

	Runoff (mm)	Soil loss (t/ha)
Continuous	38.1	47.4
Discontinuous	34.3 (−10.0)	49.6 (+4.6)

Figures in ( ) are the % changes from the result with a continuous storm.

EUROSEM estimated runoff and soil loss rates for continuous and discontinuous rainfall are shown in Table 6.2. With continuous rainfall, EUROSEM generated more runoff than with discontinuous rainfall. Also, EUROSEM estimated more soil loss with continuous rainfall than with discontinuous rainfall. The runoff and soil loss rate decreases 11.9 and 12.7 percent, respectively, with a discontinuous storm in comparison to the soil loss rate with a continuous storm.

Table 6.2 EUROSEM estimated runoff and soil loss with continuous and discontinuous rainfall for each hillslope

	Runoff (mm)	Soil loss (t/ha)
Continuous	28.7	11.0
Discontinuous	25.3 (−11.9)	9.6 (−12.7)

Figures in ( ) are the % changes from the result with a continuous storm.

RillGrow estimated soil loss rates for continuous and discontinuous rainfall are shown in Table 6.3. RillGrow generated less runoff with continuous rainfall than with discontinuous rainfall. With discontinuous rainfall, runoff actually increased 0.2 percent. However, RillGrow estimated more soil loss with continuous rainfall than with discontinuous rainfall. The soil loss rate decreases 1 percent with a discontinuous storm

in comparison to the soil loss rate with a continuous storm. Magnitudes of changes for runoff and soil loss are very small compared to WEPP and EUROSEM results.

Table 6.3 RillGrow simulated runoff and soil loss with continuous and discontinuous rainfall

	Totals lost from edges† (litre)	Soil loss (t/ha)
Continuous	471.5	91.2
Discontinuous	472.4 (+0.2)	90.3 (−1.0)

† No infiltration was considered. Every rain runs off the edge of the simulated plot. Figures in ( ) are the % changes from the result with a continuous storm.

6.4 Discussion

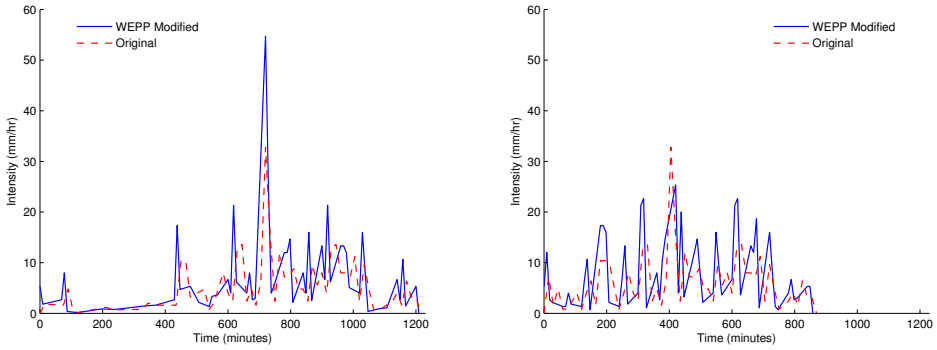
This investigation clearly shows the effect of removing WSPs during data preparations for erosion simulations. By removing WSPs, we are unintentionally creating a rainfall event with higher average intensity than original average intensity as total storm duration becomes shortened. This decreased duration means that the time given for the erosion simulation effectively decreases, resulting in smaller time values for other relevant process calculations. This may have effects on, for example, gross infiltration amounts and runoff initiation times. This alteration clearly has effects on modelling runoff and soil loss in general. In principle, removing WSPs during a storm will result in overestimated erosion rates as well as overestimated runoff. This was the case for EUROSEM simulations.

Simulation results from RillGrow runs showed very small differences between continuous and discontinuous rainfall. The differences were almost negligible. This could be caused by internal random number generator which is used for generating raindrop size. Thus, the result may imply that RillGrow is not sensitive to WSPs.

Using breakpoint data for erosion simulation will prevent the loss of WSP information. Therefore, using CLIGEN data is not recommended for studies like current

research which investigates effects of rainfall intensity changes on soil erosion. However, using breakpoint data for continuous long-term simulation is realistically very difficult since preparing such input for erosion modelling is a very labour intensive and tedious task.

WEPP estimated more soil loss for discontinuous rainfall than continuous rainfall. This was unexpected. In theory, rainfall with a higher average rainfall intensity with the same amount, hence shorter duration is expected to produce more soil loss than rainfall with a low average intensity. However, the opposite results were observed. This is because WEPP changed the intensity of the original breakpoint data used for the simulation. When time intervals shorter than an hour were used, WEPP reconstructs breakpoint data from the original breakpoint data to "WEPP-interpreted" breakpoint data, which have different intensity information from original data. Accumulated rainfall amount and the number of breakpoints are the same, but because the time increments are changed by WEPP, rainfall intensity of the original breakpoint data has been changed. WEPP increased intensity peaks of discontinuous rainfall while it decreased intensity peaks of continuous rainfall (Figure 6.3).



(a) Discontinuous **(b)** Continuous

Figure 6.3 Original rainfall intensity and WEPP-modified rainfall intensity for discontinuous and continuous rainfall.

WEPP elongates the peak intensity of discontinuous rainfall from 32.8 mm/hr to 54.7

mm/hr (Figure 6.3). This is about a 66.8% increase in peak intensity. Since the rainfall amount and total duration of discontinuous rainfall were kept almost the same, the average rainfall intensity for the original (4.4 mm/hr) and WEPP modified (4.5 mm/hr) rainfall were also similar.

This explains why WEPP estimated more soil losses for discontinuous rainfall.

6.5 Conclusion

WSPs (Within-Storm Pauses) affected runoff and soil erosion simulations by WEPP and EUROSEM. However, RillGrow showed almost no changes in runoff and soil erosion simulations. Although it was not evident to conclude whether WSPs have positive or negative effects on runoff and soil erosion estimations, removing WSPs from rainfall data is not recommended for a study like this research.

Analyses of outputs from WEPP simulations revealed new problem. WEPP modifies original rainfall intensity data and simulates erroneous results. When breakpoint data with time scales shorter than 60-min temporal scale is used for WEPP simulations, WEPP will re-construct the rainfall data so that original rainfall intensity information is lost. Particularly, peak rainfall intensity will be altered and shapes of rainfall storm will be changed. This clearly is a major problem for current research as well as a major model fault for WEPP. This means that, even if 15-min breakpoint rainfall data, as suggested in the previous chapter, are used for WEPP simulations, rainfall data that WEPP actually uses for the simulation will have different rainfall intensity.

Chapter 7

EFFECT OF WITHIN-STORM RAINFALL INTENSITY CHANGES ON SOIL EROSION

7.1 Introduction

This chapter investigates the effect of rainfall intensity changes within storm duration. WSIP (Within-Storm Intensity Pattern) means the temporal shape of the storm's WSIV (Within-Storm Intensity Variation). It could be increasing, decreasing or constant, or more complex. This is also related to the time-to-peak parameter in WEPP.

7.2 Simulation Data and Methods

A design storm was used. Rainfall intensity of the storm varied to increasing, decreasing, increasing-decreasing and constant while keeping the amount of rainfall unchanged. Only one peak intensity per storm was assumed for model simulations.

Two designed storms with average intensity of 10mm/hr (120 mm for 12 hrs) and 60 mm/hr (120 mm for 2 hrs) were used for WEPP and EUROSEM simulations. A designed storm with average rainfall intensity of 120 mm/hr was used for RillGrow simulation.

The effects of these intensity changes on runoff and soil loss rate were investigated using three models—WEPP, EUROSEM and RillGrow. WEPP, EUROSEM and RillGrow are used to simulate runoff and soil loss, and the effects of patterns were compared.

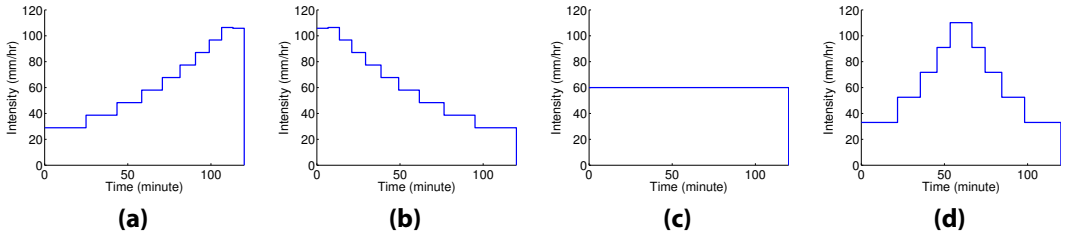


Figure 7.1 Intensity patterns of a convective storm for WEPP and EUROSEM simulations. All the inputs have the same total rainfall amount (120 mm) and duration (2 hour). Note the scales of the axes.

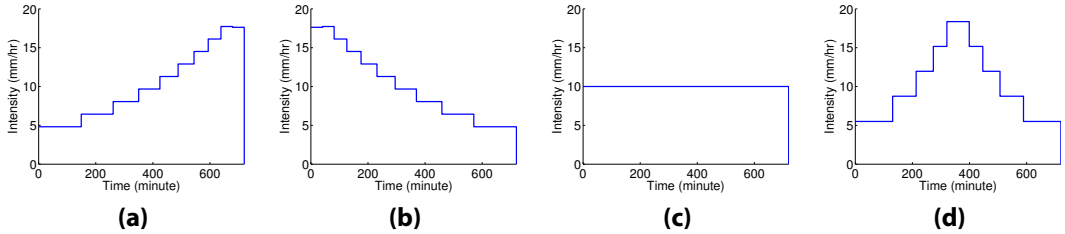


Figure 7.2 Intensity patterns of a stratiform storm for WEPP and EUROSEM simulations. All the inputs have the same total rainfall amount (120 mm) and duration (12 hour). Note the scales of the axes.

7.3 Effects on Runoff and Soil Loss

The results of WEPP, EUROSEM and RillGrow simulations are summarised in Table 7.1, Table 7.2 and Table 7.3.

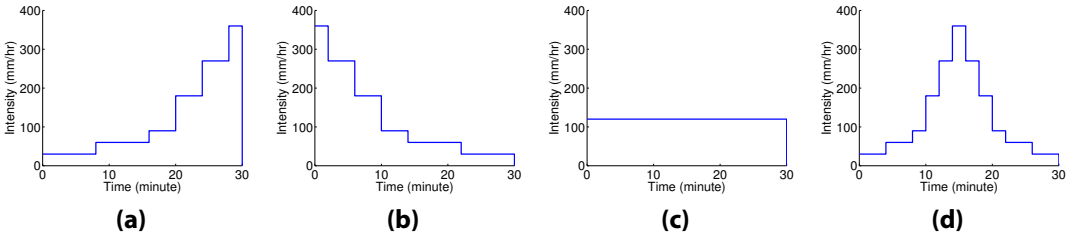


Figure 7.3 Intensity input patterns for RillGrow2 simulations. All the inputs have the same total rainfall amount and duration (i.e. 60 mm rainfall for 30 minutes). Note the scales of the axes.

Table 7.1 WEPP simulation results

Storm Pattern	60 mm/hr		10 mm/hr	
	runoff (mm)	soil loss (t/ha)	runoff (mm)	soil loss (t/ha)
Constant	104.2	105	68.9	0.4
Increasing	104.2	114.6 (+9.1)	70.3 (+2.0)	21.4 (+5250)
Decreasing	104.2	110.4 (+5.1)	68.6 (−0.4)	15.4 (+3750)
Increasing-decreasing	104.2	114.7 (+9.2)	69.9 (+1.5)	22.8 (+5600)

Figures in ( ) are the % changes from the result with a constant intensity storm. +/− indicates a increase or decrease.

Table 7.2 EUROSEM simulation results

Storm Pattern	60 mm/hr		10 mm/hr	
	runoff (mm)	soil loss (t/ha)	runoff (mm)	soil loss (t/ha)
Constant	101.4	22.6	73.8	24.7
Increasing	98.7 (−2.7)	19.7 (−12.8)	75.5 (+2.3)	22.1 (−10.5)
Decreasing	103.5 (+2.1)	22.2 (−1.8)	74.0 (+0.3)	24.1 (−2.4)
Increasing-decreasing	103.3 (+1.9)	21.0 (−7.1)	76.0 (+3.0)	22.7 (−8.1)

Figures in ( ) are the % changes from the result with a constant intensity storm. +/− indicates a increase or decrease.

Table 7.3 RillGrow simulation results

	Totals lost from edges† (litre)	Soil Loss (t/ha)
Constant	471.9	64.0
Increasing	472.4 (+0.1)	73.5 (+14.8)
Decreasing	471.2 (−0.2)	90.5 (+41.4)
Increasing-decreasing	472.2 (+0.1)	82.6 (+29.1)

† No infiltration was considered. Every rain runs off the edge of the simulated plot. Figures in ( ) are the % changes from the result with a constant intensity storm. +/− indicates a increase or decrease.

7.4 Discussion

In WEPP, WSIP is parameterized as t_p which represents normalised time-to-peak. This value was considered not much sensitive previously (Nearing *et al.*, 1990).

In this investigation, it is clear that WSIP is important for soil erosion estimation. Without knowing future WSIPs, it could easily lead to erroneous results. Moreover, when average rainfall intensity (i.e. constant rainfall intensity) of low intensity events are used for erosion modelling, WEPP immensely underestimates soil loss rates by about 50 times less than average soil loss of other WISPs. This is a considerable difference in comparison to runoff values which are similar for all four cases (Table 7.1). This result with constant intensity is consistent with Parsons and Stone (2006).

Parsons and Stone (2006) conducted a lab test to investigate the effects of intra-storm patterns (WSIPs) on soil erosion. They found that the constant-intensity storm generated about 75% of the average soil loss for the variable-intensity storms.

RillGrow estimated the similar effects on soil loss as the result of Parsons and Stone (2006). RillGrow simulated, for constant intensity rainfall, about 78% soil loss from the average soil loss of other storms. It also estimated more soil loss for the storm with decreasing intensity than other storm patterns.

Table 7.4 Experiment results (From Parsons and Stone, 2006)

Storm Pattern	Clay loam		**Sandy loam**		Sandy soil		**Total**	
	runoff (l)	loss (g)	runoff (l)	loss (g)	runoff (l)	loss (g)	runoff (l)	loss (g)
Constant	131.6	523	83.4	1256	110.2	2509	325.2	4289
Increasing	108.2	748	93.0	2435	72.2	1947	273.4	5130
Decreasing	101.3	456	114.0	3230	108.3	2862	323.6	6548
Rising-falling	110.4	631	95.8	2110	114.2	3584	320.4	6324
Falling-rising[†]	103.6	629	103.9	1645	108.1	3275	315.6	5549

[†] Not used in this research since only one peak intensity is assumed for all model simulations.

WEPP, EUROSEM and RillGrow results with varying WSIPs are compared with the result from Parsons and Stone (2006) in Table 7.5.

Table 7.5 Magnitude of soil loss affected by WSIPs

Soil Loss	Parsons and Stone (2006) (Sandy loam)	WEPP (Mean)	EUROSEM (Mean)	RillGrow
High	decreasing	increasing-decreasing	constant	decreasing
⇑	increasing	increasing	decreasing	increasing-decreasing
⇓	increasing-decreasing	decreasing	increasing-decreasing	increasing
Low	constant	constant	increasing	constant

When WEPP,for example, is to be used for erosion estimations, it is necessary to know t_p and i_p values of the rainfall storm for the simulation. As can be seen in Table 7.1, the presence of t_p have some effects on the result of simulations. It becomes more evident when rainfall with low intensity is considered.

Nearing *et al.* (1990) performed sensitivity analysis on WEPP, which was still in the process of development, by assessing various input variables such as soil, plant residue and canopy, hillslope topography, and hydrologic input variables. They calculated sensitivity parameter, S, as a relative normalised change in output to a normalised change in input. They concluded that peak rainfall intensity, time to peak rainfall intensity, rill spacing and width, and sediment transportability were not playing a major role in soil loss predictions.

Because of the fact that their analysis was carried out on the developing version of WEPP and this chapter used the new version of WEPP, their findings may not be

compared directly with the result presented in this chapter. However, it is interesting to note that they used relatively high rainfall intensity as a base value for the single storm model input parameter. They used 100 mm/hr intensity while 10 and 60 mm/hr were used for the analysis carried out in this chapter.

However, when there is no peak intensity, in other words, when intensity is constant, considerably less soil loss was generated in comparison to the ones with a intensity peak. This shows a problem in using RCM rainfall data directly for soil erosion modelling because they usually comes as daily data.

7.5 Conclusion

WSIP affects the soil erosion amount. Runoff does not seem to be affected by WSIP changes. WSIP of events with high intensity have less influence on erosion rate. Events with a constant low intensity produced dramatically less erosion. This results is consistent with the lab experiment and modelling.

7.6 Summary of Model Simulation Results

In Part II, *Rainfall Intensity and Erosion: Model Descriptions and Responses*, it has been highlighted that, in order to estimate the effect of rainfall intensity changes on future erosion, what data information we need. During the series of investigations, we have found:

- Chapter 5:
  - Temporal scales of rainfall data are closely related to the results of runoff and soil loss modelling
  - High resolution CLIGEN data generally yield more runoff and soil loss

  - Temporal scales of rainfall data affect estimations of soil loss more than runoff
  - Effects of the temporal data scale is greater for the summer rainfall event (event on 4 July 2000)
  - For the purpose of soil erosion simulation, 15-min breakpoint rainfall data are chosen
  - It may be suggested to use breakpoint data for the further simulations in this research

- Chapter 6:
  - WSPs (Within-Storm Pauses) affected runoff and soil erosion simulations by WEPP and EUROSEM.
  - RillGrow showed almost no changes in runoff and soil erosion simulations.
  - Although it was not evident to conclude whether WSPs have positive or negative effects on runoff and soil erosion estimations, EUROSEM simulated decreased runoff and soil loss rates with rainfall data with WSPs.
  - Analyses of outputs from WEPP simulations revealed new problem.
  - WEPP modifies original rainfall intensity data and simulates erroneous results.
  - When breakpoint data with time scales shorter than 60-min temporal scale is used for WEPP simulations, WEPP will re-construct the rainfall data so that original rainfall intensity information is lost.

- Chapter 7:
  - WSIP affects the soil erosion amount.
  - Runoff does not seem to be affected by WSIP changes.

- WSIP of events with high intensity have less influence on erosion rate.
- Events with a constant low intensity produced dramatically less erosion.
- This results is consistent with the lab experiment and modelling.

The effects of rainfall intensity changes on runoff and soil erosion found in Part II are summarised in Table 7.6.

7.7 Limitations of Erosion Models

In CLIGEN, the rainfall duration is an artificial abstraction that is the duration, that is a composite rainfall event with a triangular shape, calculated by summing up all the rainfall that occurred in 24 hours. CLIGEN's rainfall 'duration' is also not a realistic concept for rainstorms, which last for more than 24 hours. The unrealistic definition of CLIGEN's rainfall duration can therefore be prone to unrealistic simulation of soil erosion. CLIGEN data assumes that there is only one peak per storm. Each storm starts and ends within a 24 hour period. This means all the storms are daily.

It is thus suggested that predictions of soil erosion may be improved if we consider rainfall as an event-by-event rather than on a daily basis. In other words, rather than taking a whole wet-day (24 hours) as one "event", we may need to seek a way of separating rainfall events independent of the day. In this way, soil erosion estimations for the area with dominantly low rainfall intensity may be improved.

WEPP usually requires four stages of rainfall data conversion in order to simulate runoff and soil loss:

1. Starting with the original time step rainfall data
2. Converting to an aggregated time stepped rainfall data by removing no rainfall periods

Table 7.6 Summary of the effect of intra-storm characteristics on runoff and soil erosion

Intensity Pattern		Erosion Model			Measurement
		WEPP[1]	EUROSEM[1]	RillGrow	Parsons and Stone (2006)[2]
Constant	Runoff	–	–	–	–
	Soil loss	–	–	–	–
Increasing[†]	Runoff	–	–	–	▲▲
	Soil loss	▲ ▲ ▲	▽▽	▲▲	▲ ▲ ▲ ▲ ▲
Decreasing[†]	Runoff	–	▽	–	▲ ▲ ▲▲
	Soil loss	▲ ▲ ▲	▽	▲ ▲ ▲▲	▲ ▲ ▲ ▲ ▲
Increasing-Decreasing[†]	Runoff	–	▽	–	▲▲
	Soil loss	▲ ▲ ▲▲	▽▽	▲ ▲ ▲	▲ ▲ ▲ ▲ ▲
Continuous	Runoff	–	–	–	n/a
	Soil loss	–	–	–	n/a
Discontinuous[‡]	Runoff	▽▽	▽▽	–	n/a
	Soil loss	▲	▽▽	–	n/a

[1] Mean runoff and soil loss rate at the average intensity of 60 mm/hr and 10 mm/hr; [2] Runoff and soil loss rate for Constant Intensity was measured on a experiment plot filled with sandy loam at an average intensity of 93.9 mm/hr; [†] Magnitude of changes in comparison with Constant Intensity; [‡] Magnitude of changes in comparison with Continuous Intensity; –: unchanged or ≥1% changed; ▲: 1< Δ ≥5% increase; ▲▲: 5< Δ ≥15% increase; ▲ ▲ ▲: 15< Δ ≥30% increase; ▲ ▲ ▲▲: 30< Δ ≥40% increase; ▲ ▲ ▲ ▲ ▲: >40% increase; ▽: 1< Δ ≥5% decrease; ▽▽: 5< Δ ≥15% decrease; ▽ ▽ ▽: 15< Δ ≥30% decrease; ▽ ▽ ▽▽: 30< Δ ≥50% decrease; ▽ ▽ ▽ ▽ ▽: >40% decrease

3. Parametrising the rainfall data into amount, duration, time to peak and peak intensity
4. Finally, regenerating disaggregated rainfall data based on the parameters

After each stage, original rainfall intensity information is lost and distorted as this research has shown. When the details are lost, it is prone to lead to wrong simulation results. It is paramount to maintain intensity details such as the number of intensity peaks that occur during a storm period regardless of frequency in order to study how these intensity peaks might affect the erosion process. Assuming just one peak per storm is also a rather crud way of dealing rainfall intensity changes within a storm.

It seems that the unit conversion error is a very common problem for soil models and therefore need to be closely monitored. A clear statement of what unit is used for the specific parameter is very important. Imperial and metric units should not be used concurrently in any case. It is a simple mistake but can cause seriously erroneous estimates of runoff and soil erosion.

WEPP and EUROSEM do not consider temporal variations in erodibility during a rainfall storm. Kinnell (2005*a*) also pointed out this problem with WEPP and EUROSEM. In the case of raindrop-impact-induced erosion, current so-called process-based erosion models appear to represent the process involved inadequately in some respects because the process involved in detachment and transport of soil from the surface during experiments leading to model parametrization is unknown (Kinnell, 2005*a*).

Chapter 8

FURTHER STUDY ON TEMPORAL INTENSITY VARIATION

8.1 Aim

This experiment is to investigate impacts of *temporal intensity variations* on runoff and soil loss generations using WEPP and EUROSEM.

The questions I would like to address here are:

1. Why do we need rainfall data with higher temporal resolution for erosion modelling?
2. Then, how high is high enough resolution for erosion modelling?

8.2 Method

- Take BP data of both rain storms (July + October) – only October storm for the moment.

- Starting from 15-min (since 1- and 5-min are not possible for WEPP and EUROSEM because of too many breakpoints) to 60-min. (i.e. 15-, 30-, 60-min data)
- Original data may have high temporal variability between breakpoint to breakpoint.
  - Let's assume that we only can record rainfall data with a single fixed temporal resolution, say 15-min to start with.
  - When intensity changes rapidly, temporal variability of the intensity between BP to BP is high, so that higher temporal resolution *may* be required.
  - On the other hand, when intensity changes slowly, temporal variability of the intensity between BP to BP will be low. Therefore, higher temporal resolution *may not* be required.
- Sort data to "ascending" (Sorted-ascending) and "descending" (Sorted-descending) order to reduce the temporal variability. This means the sorted data will not have any no-rain phases within the storm duration. Thus, no-rain phase in the original rainfall data may also need to be removed to minimize possible effects from the no-rain phases (Original Rainfall (no-gaps)).
- Total rainfall amounts are the same for all the modified data (133.8 mm)
- Are the duration also the same? – no, they are different.
  - They are different because all the no-rain periods have been removed.
  - Thus, re-sorted data have shorter storm duration compared to original.
  - 1215, 1230 and 1260 min for 15-min, 30-min and 60-min original data
  - 930, 1020 and 1080 min for 15-min, 30-min and 60-min sorted and original-without-gaps data

8.3 Result

1. When rainfall data is re-sorted, some of the storm character is modified (shape of the storm and duration). Also, number of breakpoint may need to be recalculated (not done as it may not be important for this stage – pilot test was done, and for the WEPP simulation, it makes a difference because of how WEPP deals with breakpoint. It re-calculates time of breakpoints!)

    - Original data vs. Sorted data (unchanged breakpoints)
    - Sorted data (unchanged breakpoints) vs. Sorted data (redefined breakpoints) – see the comments above.
    - Original data vs. Sorted data (redefined breakpoints) – not done, far from the pilot test.
    - Thus, resulting runoff and soil loss estimations may differ when BP was redefined.
    - For the moment, I only looked at 1?

2. October storm

    - Original data
        - Amount: 133.8 mm
        - Duration: 1209 min (for 15-min data)
    - Modified data (ascending, descending and original-without-gaps)
        - Amount: 133.8 mm
        - Duration: 942 min (for 15-min data)

Table 8.1 WEPP simulations with October rainfall data

WEPP with October Storm			D	E	F	G	H	I	J	K	L	MEAN	% Δ from original
15-min	runoff (mm)	original	63.9	63.6	71.1	81.8	86.4	86.4	86.4	71.7	71.7	75.9	
		original-nogap	64.8	64.4	72.3	80.8	85.0	85.0	85.0	72.7	72.7	75.9	
		sorted-ascending	77.2	76.9	80.6	86.1	88.6	88.6	88.6	80.8	80.8	83.1	9.5
		sorted-descending	73.7	73.4	76.5	81.8	84.4	84.4	84.4	76.7	76.7	79.1	4.2
	soil loss (t/ha)	original	37.7	36.8	95.3	145.2	175.3	167.6	148.2	86.8	77.5	107.8	
		original-nogap	46.8	49.2	105.9	152.5	180.6	171.5	151.7	94.2	85.4	115.3	
		sorted-ascending	60.0	62.1	121.9	164.8	190.4	181.4	161.0	108.1	96.1	127.3	18.1
		sorted-descending	50.5	52.2	109.9	155.7	181.9	173.1	153.8	101.8	90.8	118.8	10.2
30-min	runoff (mm)	original	68.5	67.9	72.7	77.5	79.8	79.8	79.8	72.8	72.8	74.6	
		original-nogap	67.5	67.2	74.8	80.9	83.1	83.1	83.1	75.2	75.2	76.7	
		sorted-ascending	78.0	77.7	80.1	82.3	83.5	83.5	83.5	80.2	80.2	81.0	8.6
		sorted-descending	74.1	73.8	76.2	77.9	79.1	79.1	79.1	76.3	76.3	76.9	3.0
	soil loss (t/ha)	original	45.0	43.8	101.4	141.1	165.3	154.5	141.0	92.7	83.9	107.6	
		original-nogap	25.2	24.6	85.9	129.3	155.1	149.1	132.5	73.8	61.4	93.0	
		sorted-ascending	57.0	58.5	117.1	154.7	177.3	169.4	150.6	105.8	94.9	120.6	12.1
		sorted-descending	43.7	43.9	102.7	138.9	160.8	153.2	134.9	91.5	80.9	105.6	−1.9
60-min	runoff (mm)	original	69.9	69.4	74.2	76.6	77.3	77.3	77.3	74.3	74.3	74.5	
		original-nogap	69.9	69.4	74.2	76.6	77.3	77.3	77.3	74.3	74.3	74.5	
		sorted-ascending	75.0	74.8	77.2	78.4	78.8	78.8	78.8	77.2	77.2	77.3	3.8
		sorted-descending	71.5	71.2	73.6	74.8	75.2	75.2	75.2	73.7	73.7	73.8	−1.0
	soil loss (t/ha)	original	16.9	15.7	73.1	112.8	134.0	124.2	103.9	59.6	46.7	76.3	
		original-nogap	16.9	15.7	73.1	112.8	134.0	124.2	103.9	59.6	46.7	76.3	
		sorted-ascending	18.8	17.7	76.9	116.1	137.2	127.3	106.5	62.7	49.3	79.2	3.7
		sorted-descending	8.0	5.1	58.9	97.8	119.0	109.3	89.0	47.3	35.2	63.3	−17.1

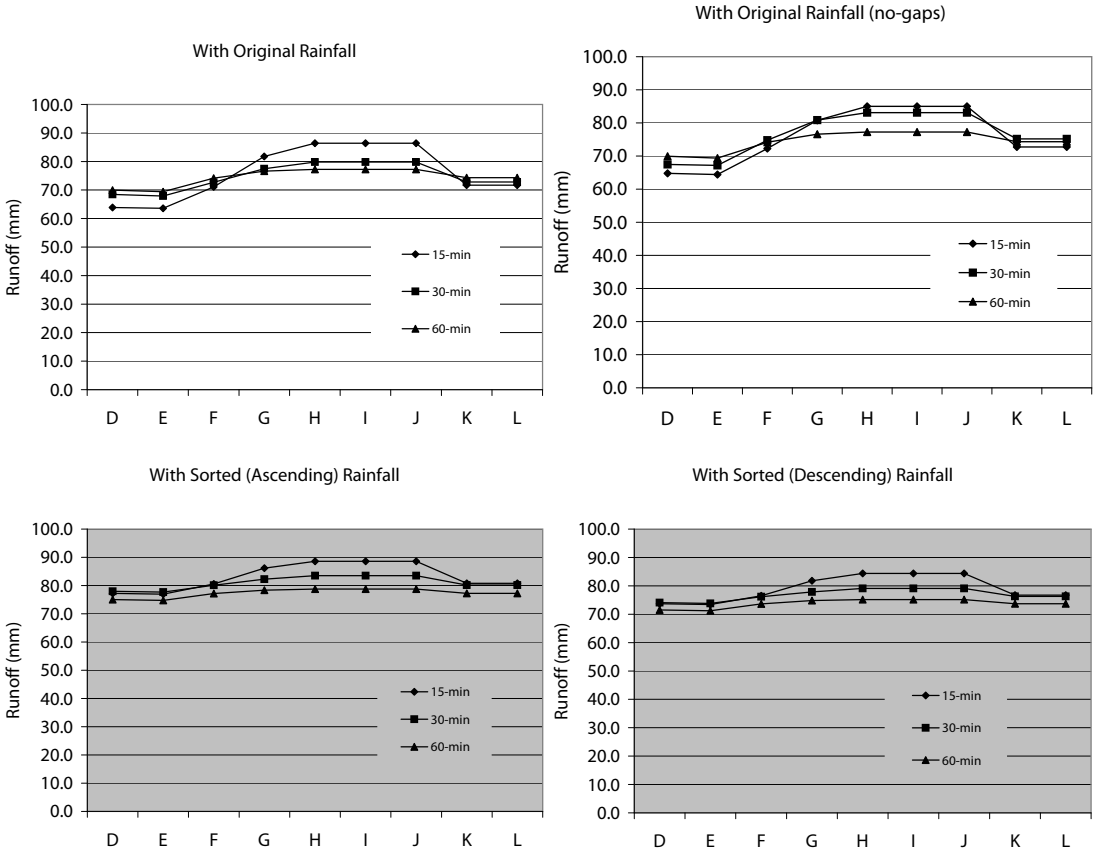


Figure 8.1 WEPP simulated runoff rates with original and sorted October rainfall data

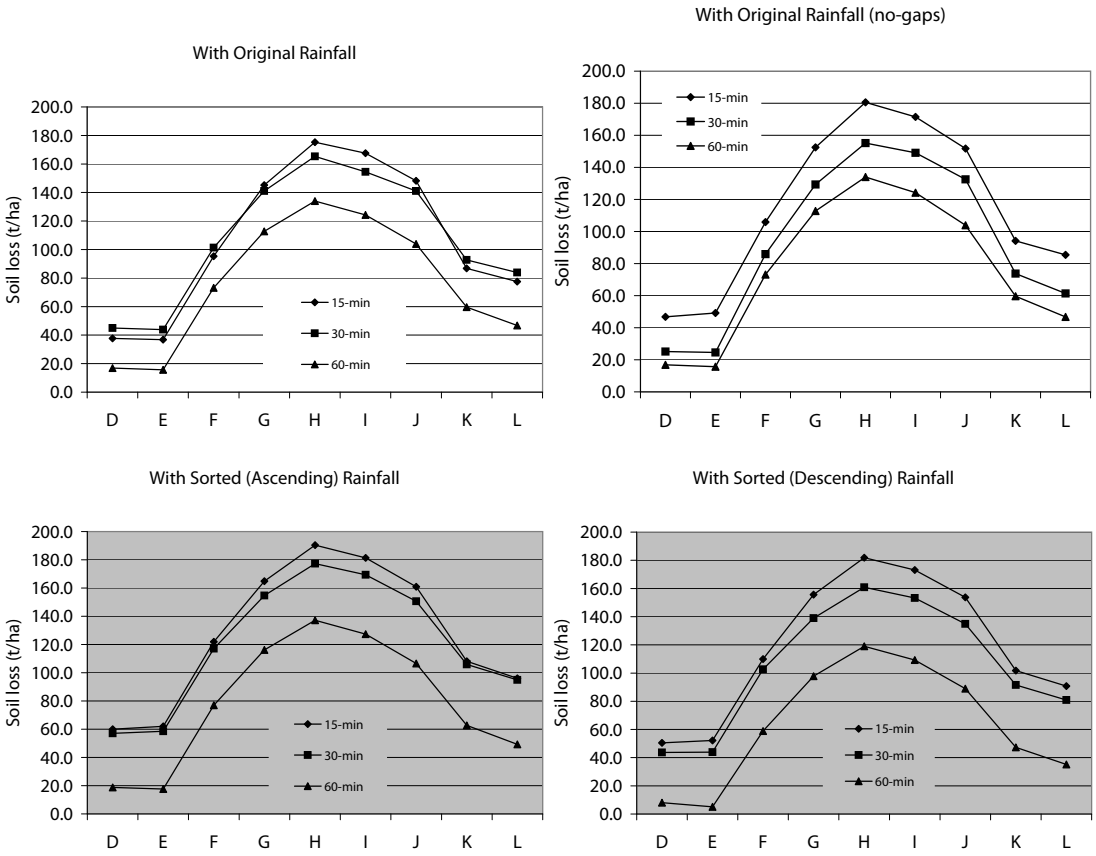


Figure 8.2 WEPP simulated soil loss rates with original and sorted October rainfall data

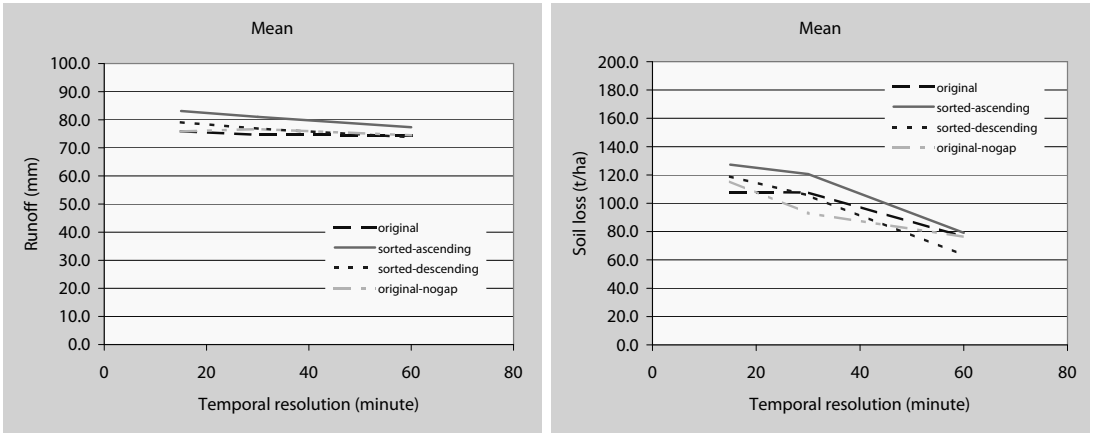


Figure 8.3 WEPP simulated mean runoff and soil loss rates with different temporal data resolutions

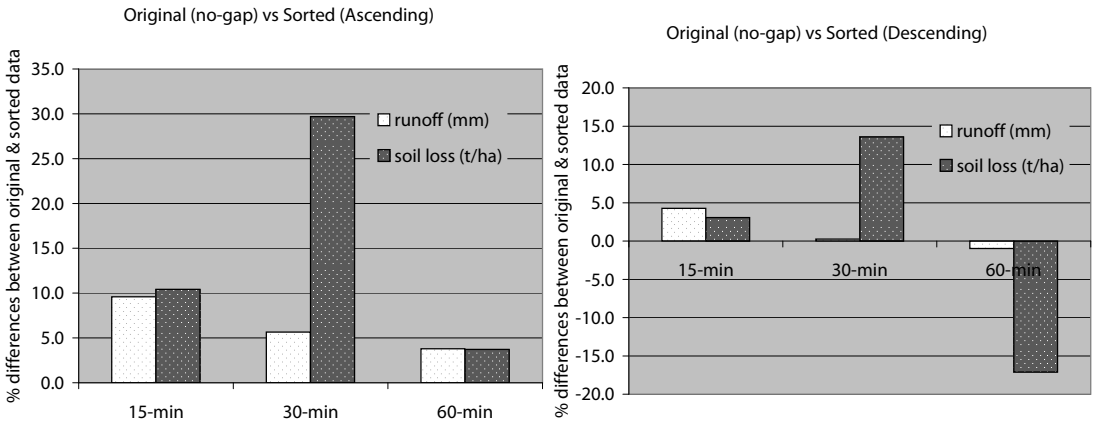


Figure 8.4 Changes in WEPP simulated runoff and soil loss rates using original and sorted rainfall data for different temporal data resolution

8.3.1 WEPP simulation

8.3.2 EUROSEM simulation

8.4 Discussion

Things that I need to discuss:

- Only 15-, 30-, and 60-min temporal resolutions used because of the limitation on the number of breakpoints that WEPP can take
- Try to minimise possible effects from other factors (gaps, rainfall amount, duration, shape of the storm, etc.)
- Re-sorting the data will results in "increasing-intensity" storm or "decreasing-intensity" storm. Thus, the effects from the differences in temporal intensity variation may be only applicable for whichever storm shape we used, in this case "increasing-intensity".
- The differences I may see here may be the results of models' artefacts.

Table 8.2 EUROSEM simulations with October rainfall data

EUROSEM with October Storm			D	E	F	G	H	I	J	K	L	MEAN	% Δ from original
15-min	runoff (mm)	original	62.9	62.9	63.0	63.2	63.4	63.3	63.2	63.0	63.0	63.1	
		original-nogap	70.3	70.2	70.3	70.6	70.8	70.7	70.6	70.3	70.3	70.5	
		sorted-ascending	82.9	82.7	83.1	83.2	83.6	83.4	83.4	83.2	83.3	83.2	31.9
		sorted-descending	84.2	84.2	84.4	84.5	84.6	84.5	84.4	84.3	84.3	84.4	33.7
	soil loss (t/ha)	original	19.3	19.3	26.4	39.1	59.0	43.9	36.6	23.3	22.0	32.1	
		original-nogap	21.8	21.8	29.7	43.6	66.0	49.1	40.8	26.3	24.8	36.0	
		sorted-ascending	22.5	22.4	30.7	46.9	72.5	53.3	44.3	27.4	26.0	38.4	19.8
		sorted-descending	25.1	25.1	34.2	49.3	77.6	56.2	46.2	30.5	28.8	41.4	29.2
30-min	runoff (mm)	original	69.4	69.3	69.5	69.6	69.7	69.6	69.6	69.5	69.4	69.5	
		original-nogap	71.4	71.4	71.6	71.7	71.8	71.7	71.7	71.5	71.5	71.6	
		sorted-ascending	80.1	79.9	80.3	80.4	80.7	80.6	80.6	80.4	80.5	80.4	15.6
		sorted-descending	80.8	80.8	81.0	81.1	81.2	81.0	81.0	80.9	80.9	80.9	16.4
	soil loss (t/ha)	original	21.9	21.8	29.8	41.5	64.8	46.5	38.8	26.5	25.1	35.2	
		original-nogap	22.8	22.8	31.1	43.0	67.0	48.0	40.1	27.7	26.2	36.5	
		sorted-ascending	23.7	23.5	32.1	44.9	72.5	51.4	42.2	28.7	27.2	38.5	9.4
		sorted-descending	26.2	26.1	35.8	47.0	77.1	53.7	43.8	31.9	30.2	41.3	17.5
60-min	runoff (mm)	original	74.4	74.4	74.6	74.6	74.8	74.7	74.6	74.5	74.5	74.6	
		original-nogap	75.5	75.5	75.7	75.8	75.9	75.8	75.8	75.6	75.6	75.7	
		sorted-ascending	78.2	78.1	78.4	78.5	78.8	78.7	78.7	78.5	78.6	78.5	5.3
		sorted-descending	77.9	77.9	78.1	78.2	78.3	78.2	78.1	78.0	78.0	78.1	4.7
	soil loss (t/ha)	original	23.3	23.2	31.8	43.5	69.8	50.2	40.6	28.3	26.8	37.5	
		original-nogap	24.0	23.9	32.8	44.7	71.2	51.4	41.7	29.2	27.6	38.5	
		sorted-ascending	24.2	24.1	33.0	44.6	72.3	51.4	41.8	29.5	27.9	38.8	3.4
		sorted-descending	26.8	26.7	36.7	46.4	75.6	53.2	43.1	32.7	31.0	41.4	10.3

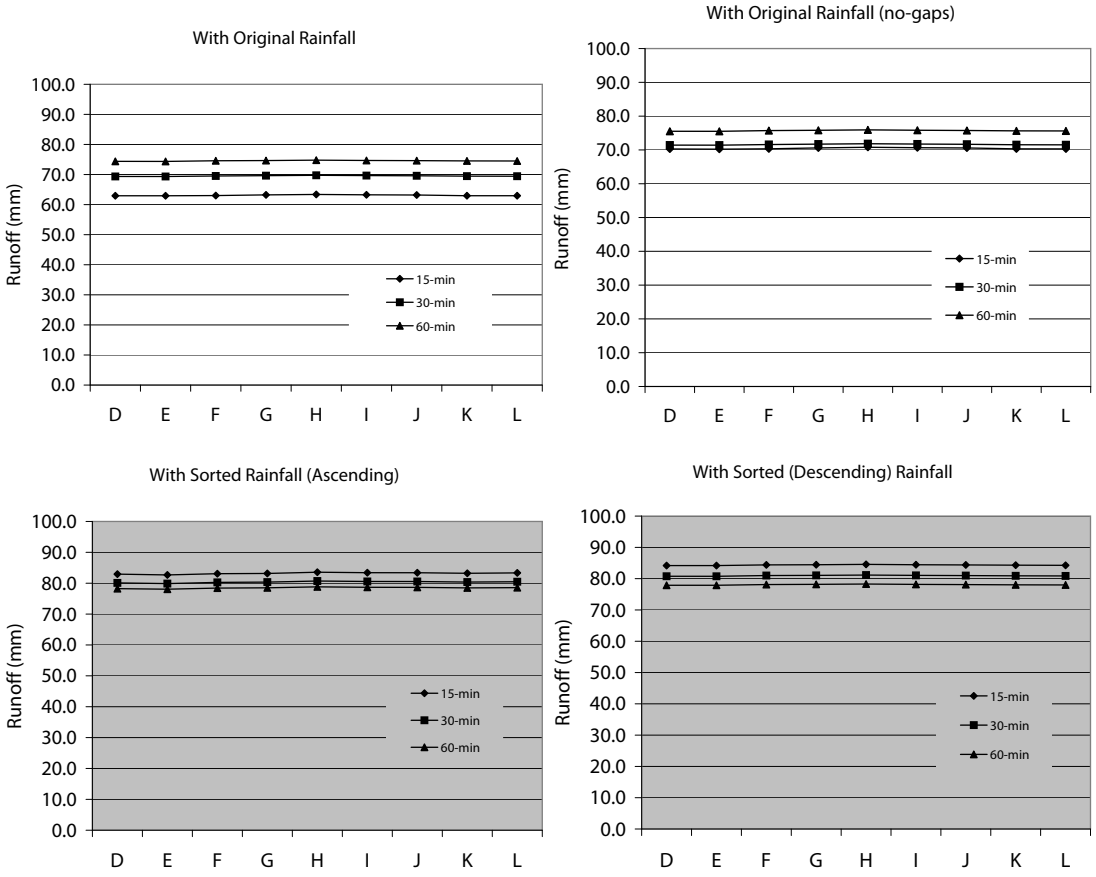


Figure 8.5 EUROSEM simulated runoff rates with original and sorted October rainfall data

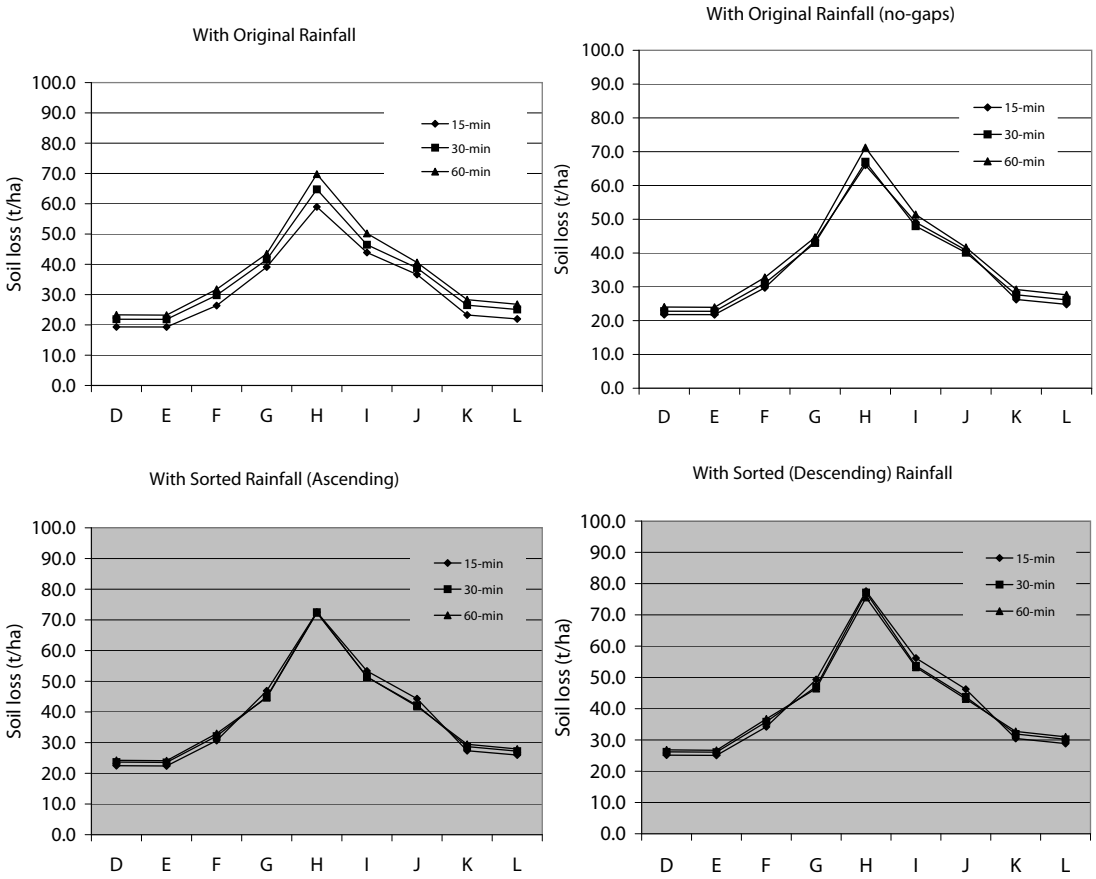


Figure 8.6 EUROSEM simulated soil loss rates with original and sorted October rainfall data

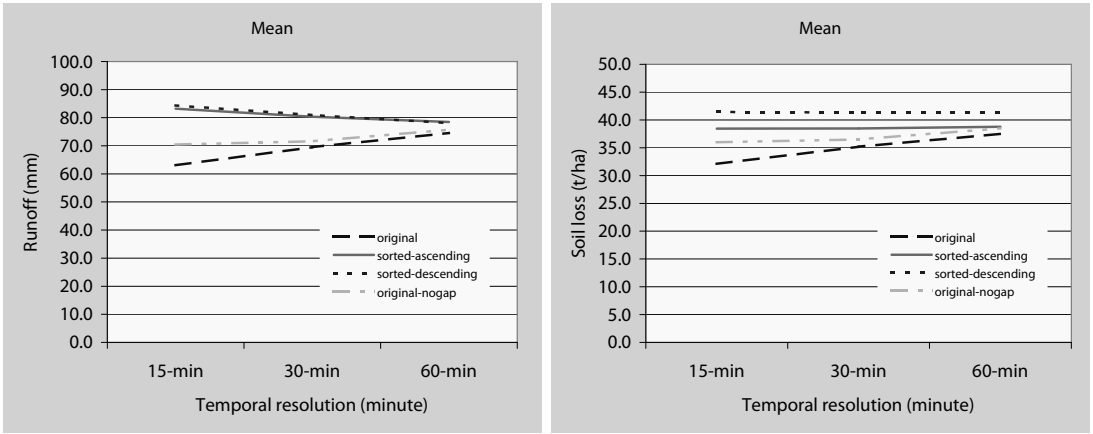


Figure 8.7 EUROSEM simulated mean runoff and soil loss rates with different temporal data resolutions

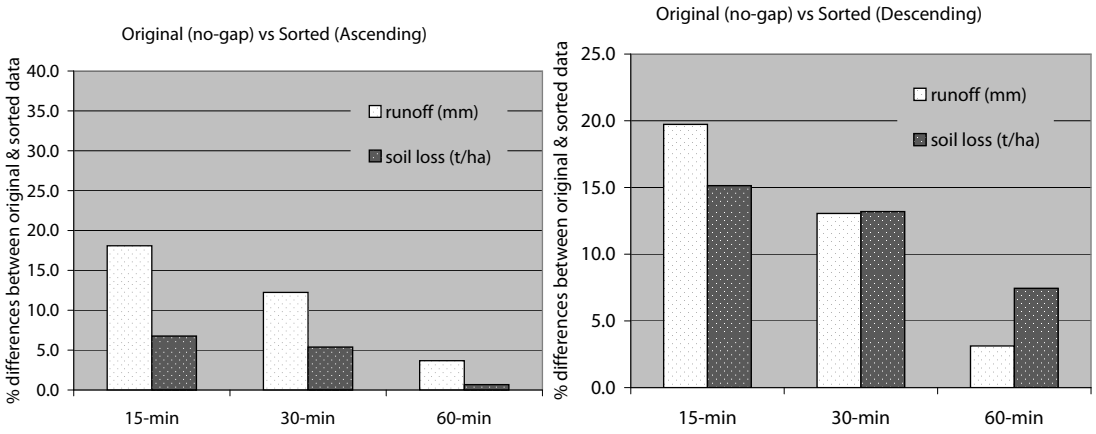


Figure 8.8 Changes in EUROSEM simulated runoff and soil loss rates using original and sorted rainfall data for different temporal data resolution

- …

For EUROSEM simulation, each slope has been flattened to have a uniform slope angle.

The original rainfall data have no-rain phases which might have affected runoff and soil loss rate simulations. This may be the case for the simulations with sorted-descending rainfall data. From the charts (Chart1-3 in WEPP-outputs.xls), the simulated soil loss rate with sorted-descending rainfall data show higher soil loss rate for 15-min, similar for 30-min, and less for 60-min than the ones with original rainfall.

Runoff and soil loss rates with sorted-ascending rainfall data and sorted-descending rainfall data seems running parallel to each other (see Chart1-2 in WEPP-outputs.xls).

Sorted-descending and sorted-ascending rainfall data have the same rainfall duration as well as rainfall amount.

Thus, original without the gaps were subjected to the same simulations. The modified original rainfall data have the same rainfall duration as sorted data.

For WEPP, rainfall data with higher bp-to-bp variability (original rainfall data) resulted in less affected runoff and soil loss rates by temporal resolution. – quantify

this! Runoff and soil loss rate with original rainfall has low β value (from $y = \beta x + \alpha$).

For EUROSEM, rainfall data with higher bp-to-bp variability (original) showed more affected runoff and soil loss rates by temporal resolution. – quantify this! Runoff and soil loss rate with original rainfall has high β value (from $y = \beta x + \alpha$).

Higher temporal resolution data have greater temporal variation in intensity. These variations were reduces by "sorting" the same rainfall data. The data were sorted by ascending order.

15-min resolution data showed greater differences between original & sorted

60-min resolution data showed little differences compare to the 15-min.

Proportionally soil loss rate simulated by WEPP is affected more compared to runoff.

+++++

15-min data generated higher runoff & erosion rates.

Sorted data generated more runoff & erosion.

15-min data showed greater differences between original & sorted.

High temporal resolution resulted in greater runoff & soil erosion rate for both (original & sorted).

Effects of high temporal resolution & high temporal variation is grater for erosion (Fig. 8.4) – are you sure? check this!

8.5 Additional tests

further test with different intensity and variability

8.5.1 Aims

Terms to be defined:

unsorted (original) = high (natural) breakpoint-to-breakpoint variability

sorted = low breakpoint-to-breakpoint variability

There are two way of calculating BP-to-BP Variance. One is to simply add all the values with the +/- signs. The other is to calculate RMS (root mean square) for the value. This will remove the orientation of the BP-to-BP variance.

I need to justify why I have used intensity (or amount) for breakpoint-to-breakpoint variability.

Table 8.3 Breakpoint-to-breakpoint variances calculated with rainfall amount (mm)

		15-min	30-min	60-min
Simple Addition	Original (without no-rain phase)	-0.01	-0.02	-0.04
	Sorted (Ascending)	0.1	0.31	0.92
	Sorted (Descending)	-0.1	-0.31	-0.92
Root Mean Square	Original (without no-rain phase)	2	3.56	5.44
	Sorted (Ascending)	0.2	0.45	1.16
	Sorted (Descending)	0.2	0.45	1.16

It is more appropriate to use intensity in calculating Breakpoint-to-breakpoint variance. When amount is used, for example 15-min data, breakpoint-to-breakpoint variance will be smaller than 60-min data because 15-min data has generally smaller rainfall amount for a Breakpoint-to-breakpoint time period in comparison to 60-min. Thus, direct comparison does not give valid comparison. However, when intensity is used, temporal resolution for each amount is considered so that breakpoint-to-breakpoint variance can be compared. Therefore, rainfall intensity is used for calculating breakpoint-to-breakpoint variances for each temporal resolution.

Table 8.4 Breakpoint-to-breakpoint variances calculated with rainfall intensity (mm/hr)

		15-min	30-min	60-min
Simple Addition	Original (without no-rain phase)	-0.05	-0.05	-0.04
	Sorted (Ascending)	0.39	0.62	0.92
	Sorted (Descending)	-0.39	-0.62	-0.92
Root Mean Square	Original (without no-rain phase)	8.22	7.13	5.45
	Sorted (Ascending)	0.81	0.89	1.16
	Sorted (Descending)	0.81	0.89	1.16
Mean of Sum of Absolute Values	Original (without no-rain phase)	6.19	5.67	4.47
	Sorted (Ascending)	0.39	0.62	0.92
	Sorted (Descending)	0.39	0.62	0.92

Original – RMS

This result is something that I have expected to see. Shorter the temporal resolution of data, greater the BP-to-BP variances.

Asc. & Des – RMS

These are somewhat interesting. There must be reasons to explain this. Why greater BP-to-BP variance for the longer temporal resolution data?

The total value of the variance for the 15-min data is greater than 60-min data. However, mean becomes smaller for the 15-min data than 60-min data because of the total number of data points for 15-min data.

Maximum breakpoint-to-breakpoint variability can be obtained by sorting the storm data (to ascending and descending either way) and calculating breakpoint-to-breakpoint variability. Because the breakpoint comes in next will have the smallest possible breakpoint-to-breakpoint variability and so on.

In contrast, maximum breakpoint-to-breakpoint variability can be achieved by taking one breakpoint data from the either end of the sorted data, and stack them in alternating manner.

PART III

Implications for Model-based Studies of Future Climate Change and Soil Erosion

Chapter 9

ESTIMATION OF SOIL EROSION: IMPLICATIONS FOR FUTURE RAINFALL INTENSITY

9.1 Introduction

The results described earlier in this thesis suggest that it is unlikely that we can, at present, predict future rainfall intensity changes and effects of these changes on future soil erosion with reasonable confidences. To move forward, it is necessary to acknowledge the limitations in investigating the effect of rainfall intensity changes on future erosion rates.

If we knew with certainty what the impacts of climate change would be at a local level, then adaptation would be easier; we could say this will be the impact in this location in this year, and then look at what would need to happen to avoid that impact. Unfortunately, we don't, and it is likely that we will unlikely be able to make predictions that are detailed enough and certain enough to make a 'predict and adapt' approach to

adaptation a viable option.

However, it may still be possible to draw outlines of future erosion rates using the findings from previous chapters. It may also be possible to simulate how these future rainfall intensity changes will take place and affect soil erosion.

This chapter aims to find out the impact of rainfall intensity changes on "future" soil erosion. The outcomes of this chapter aims to give answers for Research Question 4; *Are we in a position to predict erosion rates under future climates, with different rainfall intensities from the present? If not, what must be done?*

As discussed before, it is impractical to try to predict future erosion at this stage because of the lack of reliable future rainfall data and the imperfection of current erosion models that were found in the previous stages of this research. It may be argued, however, that a guideline could still be drawn out for investigating impacts of rainfall intensity changes on future erosion. In this way, when rainfall data with an acceptable confidence level and better intensity-aware erosion models become available, future erosion may be predicted with a greater certainty.

Only WEPP was utilised in this part of research because WEPP is the only continuous simulation model from three models used during this research. The other two models (EUROSEM and RillGrow) are what is known as a single event model that is only capable of dealing with a single rainfall event rather than the whole system status that is dynamically updated as the simulation continues over multiple rainfall events. A continuous simulation model—like WEPP—is required to simulate long-term erosion without failing to consider the complex overlap of temporally and spatially diverse distributions of rainfall, erodibility, soil conditions, plant cover and so on (Nearing, 2006).

9.2 Possible Methods for Simulating Future Intensity

Despite the various efforts to find meaningful rainfall intensity trend for building future scenarios of rainfall intensity changes, no significant trend can be determined from analysing observed rainfall data in the study area. Yet future rainfall intensities are predicted to increase. However, even if the trend in rainfall intensity is available (for example from an RCM), the results from this study indicate that knowing future WSIV, WSIP and WSP is vital in order to carry out future erosion predictions. To achieve the aim of this research, an alternative method has to be sought to obtain future rainfall data with a appropriate data scale and 'changed' rainfall intensity. The process of finding alternative method is discussed in this section.

9.2.1 Possible Method 1: Changing CLIGEN Generated Data

Daily peak rainfall intensity is changed by changing daily rainfall duration. In a CLIGEN output, R, D, t_p and i_p comprise daily rainfall. These are:

- R : amount (inch)
- D : duration (minute)
- t_p : time to peak (normalised)
- i_p : peak intensity (normalised)

Among these four factors, duration (D) will be adjusted proportionally, keeping other factors such as t_p, i_p and R constant. In this way, the rainfall amount is kept constant, and rainfall intensity is varied.

Thirty year-long climate data were generated using CLIGEN with an input file, which was prepared from the Southover dataset. Daily rainfall durations in this 30 year-long climate data were adjusted proportionally to obtain increased or decreased daily peak

rainfall intensities. Using the original and adjusted climate data, runoff and soil erosion were to be simulated for 30 years. The effect of *indirect* rainfall intensity changes on runoff and erosion were then analysed.

Pros: Simple, easy and fast.

Cons: It may be considered to be crude and simple for simulating future rainfall intensity changes. It does not make a full use of the findings from the previous analyses. This clearly is an indirect approach.

9.2.2 Possible Method 2: Changing MX.5P, One of CLIGEN Input Parameters

Description of MX.5P (Yu, personal communication 2003) MX.5P is defined as "Average maximum 30-min peak intensity (in/hr) for each month". If the sub-daily interval is denoted as Δt (min), then there are $1440/\Delta t$ intervals, called M_t, in a day. For each wet day, discard all the dry intervals to create a single storm event with *continuous* rain for, say, M intervals. Then the storm duration, D, (min) is given by:

$$D = M\Delta t\delta \tag{9.1}$$

Find the maximum precipitation intensity for any 30-min period within the storm, and call this I_{30}. If there are n wet days in a month, find the maximum of these n I_{30} values, and denote this maximum I_{30} for the month as $maxI_{30}$. If there are K months on record, then MX.5P is given by:

$$\text{MX.5P} = \frac{1}{K}\sum maxI_{30} \tag{9.2}$$

For example, let us say it rained on 3rd and 10th of May, 2001 with a peak 30-min intensity of 1.2 in/hr and 1.5 in/hr, respectively. Then $maxI_{30}$ would be 1.5 in/hr for May 2001. If we have 5 years of data for May:

Month	Year	$maxI_{30}$ (in/hr)
May	1997	0.8
May	1998	0.9
May	1999	0.3
May	2000	2.8
May	2001	1.5

Then the MX.5P value for May for this hypothetical site would be:

$$\frac{0.8 + 0.9 + 0.3 + 2.8 + 1.5}{5} = 1.26 \text{ (in/hr)}. \tag{9.3}$$

Changing MX.5P The CLIGEN *input* file was adjusted accordingly rather than the CLIGEN *output* file. Two CLIGEN input files were prepared as if they are from two different periods—present and future—of the site. Future climate changes are thus conceptualised here as "two different climate conditions in the same place". The original input file was built using observed event rainfall data from Ditchling Road station. Rainfall intensity parameter (MX.5P) of the original input file was adjusted accordingly to represent future rainfall intensity changes (Table 9.1). Two sets of CLIGEN generated weather data using these two input files only differ in peak rainfall intensities, which is controlled by MX.5P. Then, WEPP simulates runoff and soil loss rates using these two CLIGEN climate data.

Table 9.1 Ratio of MX.5P changes for each month

	Decrease		Increase	
Wet Season (SONDJF months)	−10%	−5%	+5%	+10%
Dry Season (MAMJJA months)	−10%	−5%	+5%	+10%

Few studies pointed out that the ratio of wet and dry days will influence the behaviour of future soil erosion (Nearing, 2001; Pruski and Nearing, 2002*a*,*b*). However, as this thesis only concentrates on the implication of rainfall intensity changes, no rainfall frequency change is considered. No rainfall amount change is also assumed here. Due to the lack of information, no intra-storm rainfall intensity pattern for the future was considered.

Nearing (personal e-mail communications, 8 June 2001) pointed out that, if MEAN P in CLIGEN input file is changed together with MX.5P, we would end up with completely different climate data from what we have started with. Also, generated data may not have clear relationships with original data. This is a problem for a sensitivity-type comparison—that is, comparing how WEPP estimates differ for two well-defined sets of input data. On the other hand, when creating "realistic" future rainfall data is to be the main concern, both parameters (MEAN P and MX.5P), together with other parameters may need to be changed. It will, however, only be applicable to the case where sufficient reference data are available for the adjustment and comparison of all the parameter. No such information has been available for this research. Therefore, until such information is available, it is important to limit the changes only to a single parameter, MX.5P in this case, and carry out the sensitivity-type comparison.

It is very unlikely all the month will have the same changes in rainfall intensity. There will be some degrees of variations depending on seasons, for example. Two seasonal variations are considered here—Wet and Dry season. The wet season includes September, October, November, December, January and February (Table 9.2). The dry season consists of March, April, May, June, July and August (Table 9.3).

Since soil erosion is closely related to the extreme rainfall events, this thesis concentrates on extreme rainfall events which are closely related to the rainfall parameter, MX.5P. This is the main reason why MX.5P is chosen to be altered. It is clear that Nicks

Table 9.2 Adjusted MX.5P values for the wet season

month	**1**	**2**	3	4	5	6	7	8	**9**	**10**	**11**	**12**
−10%	0.24	0.16	0.23	0.23	0.27	0.33	0.42	0.58	0.39	0.41	0.31	0.27
−5%	0.26	0.17	0.23	0.23	0.27	0.33	0.42	0.58	0.41	0.43	0.32	0.28
original	0.27	0.18	0.23	0.23	0.27	0.33	0.42	0.58	0.43	0.45	0.34	0.30
5%	0.28	0.19	0.23	0.23	0.27	0.33	0.42	0.58	0.45	0.47	0.36	0.32
10%	0.30	0.20	0.23	0.23	0.27	0.33	0.42	0.58	0.47	0.50	0.37	0.33

Table 9.3 Adjusted MX.5P values for the dry season

month	1	2	**3**	**4**	**5**	**6**	7	**8**	9	10	11	12
−10%	0.27	0.18	0.21	0.21	0.24	0.30	0.38	0.52	0.43	0.45	0.34	0.30
−5%	0.27	0.18	0.22	0.22	0.26	0.31	0.40	0.55	0.43	0.45	0.34	0.30
original	0.27	0.18	0.23	0.23	0.27	0.33	0.42	0.58	0.43	0.45	0.34	0.30
5%	0.27	0.18	0.24	0.24	0.28	0.35	0.44	0.61	0.43	0.45	0.34	0.30
10%	0.27	0.18	0.25	0.25	0.30	0.36	0.46	0.64	0.43	0.45	0.34	0.30

et al. (1995) has recognised the close statistical relationship between MX.5P and soil erosion rate. This may explain why this parameter is included in a CLIGEN input file.

Pros: The procedures are relatively easy and uncomplicated. Calculating MX.5P is relatively straightforward from tipping-bucket data. It does change the rainfall intensity of extreme events.

Cons: Generated rainfall data for the original and "future" climate are almost the same except for rainfall intensity. Thus the "future condition" here is not, physically, very realistic. Future climate will change in complex ways, not only extreme rainfall intensity will change, but also probabilities of raindays, WSIP (Within-Storm Intensity Pattern), and, surly rainfall amount will change. Also, even if we increase or decrease extreme rainfall intensity only, the intensity of small rainfall events are also affected in order to keep overall annual rainfall amount constant.

9.2.3 Possible Method 3: Using GCM/RCM Data

This third method described here was proposed originally, but has not been used because there were no GCM data which were suitable for this research because of the scale mismatch. Nevertheless, daily RCM data for current and future climate have been acquired. RCM also produced 20-min rainfall data, but with a high variability. Daily rainfall intensity (or amount) is not suitable to be used as erosion model input directly unless downscaled.

The procedures of this method are:

1. GCM data with 30-min time step for current and future climate
2. CLIGEN input files for current and future climate are built
3. CLIGEN generates climate data for current and future climate
4. WEPP simulates runoff and erosion for current and future climate.

It might be possible to calculate all the CLIGEN input parameters out of the GCM output. GCMs can generate current and future climate data on a sufficient time scale—that is, 30-min time step—for building CLIGEN input files. This will permit ones to make a "better" (or maybe worse) judgement of impacts of rainfall intensity changes on future soil erosion.

There are some possible caveats with this approach. One is that high resolution climate data such as highly specified GCM and RCM data are generated with the most extreme set-ups of the climate model. This will push the model to its limits. These generated data, thus, may have problems and errors caused by unconventional configurations on the top of GCMs' uncertainty and wide range of variations. Another caveat is that the high resolution data are not always readily available. A separate model configuration is required to generate this kind of data, and the set-up process involving

usually requires extended model set-up skills and simulation times. This was the case for the current research. Another possible problem is that, because of the preceding uncertainty of GCM output, we might end up with erroneous CLIGEN input files which, in turn, will lead to even greater errors for future erosion estimation.

9.2.4 Selected Method: Method 2, Changing CLIGEN Input

The Method Two (Section 9.2.2) is selected. The schematic procedure of this method is shown in Figure 9.1.

It was assumed that future WSIV, WSP and WSIP are the same as the present. Only monthly maximum of 30-min peak rainfall intensity was considered for constructing future rainfall intensity scenarios.

CLIGEN generates original climate data using the input file which statistically represents the characteristics of current rainfall intensity. Keeping all other parameters constant, the intensity parameter (MX.5P) in the CLIGEN input file are increased or decreased proportionally (Table 9.1). MX.5P is specifically related to extreme intensity events as given by its definition, 'Average maximum 30 minutes peak intensity (in/hr) for each month'. "Future" climate data are then generated using adjusted CLIGEN input file. WEPP simulates runoff and soil loss using both climate data. Runoff and soil loss changes are compared with changes in rainfall intensity.

9.3 Sensitivity of WEPP to Rainfall Intensity Changes

Before using WEPP for the current investigation, the sensitivity of WEPP to changes in rainfall intensity were tested. Rainfall intensity was modified indirectly by controlling the rainfall duration. The rainfall amount and ratio of average intensity to peak intensity were not changed. The relationship between actual peak intensity, I and rainfall

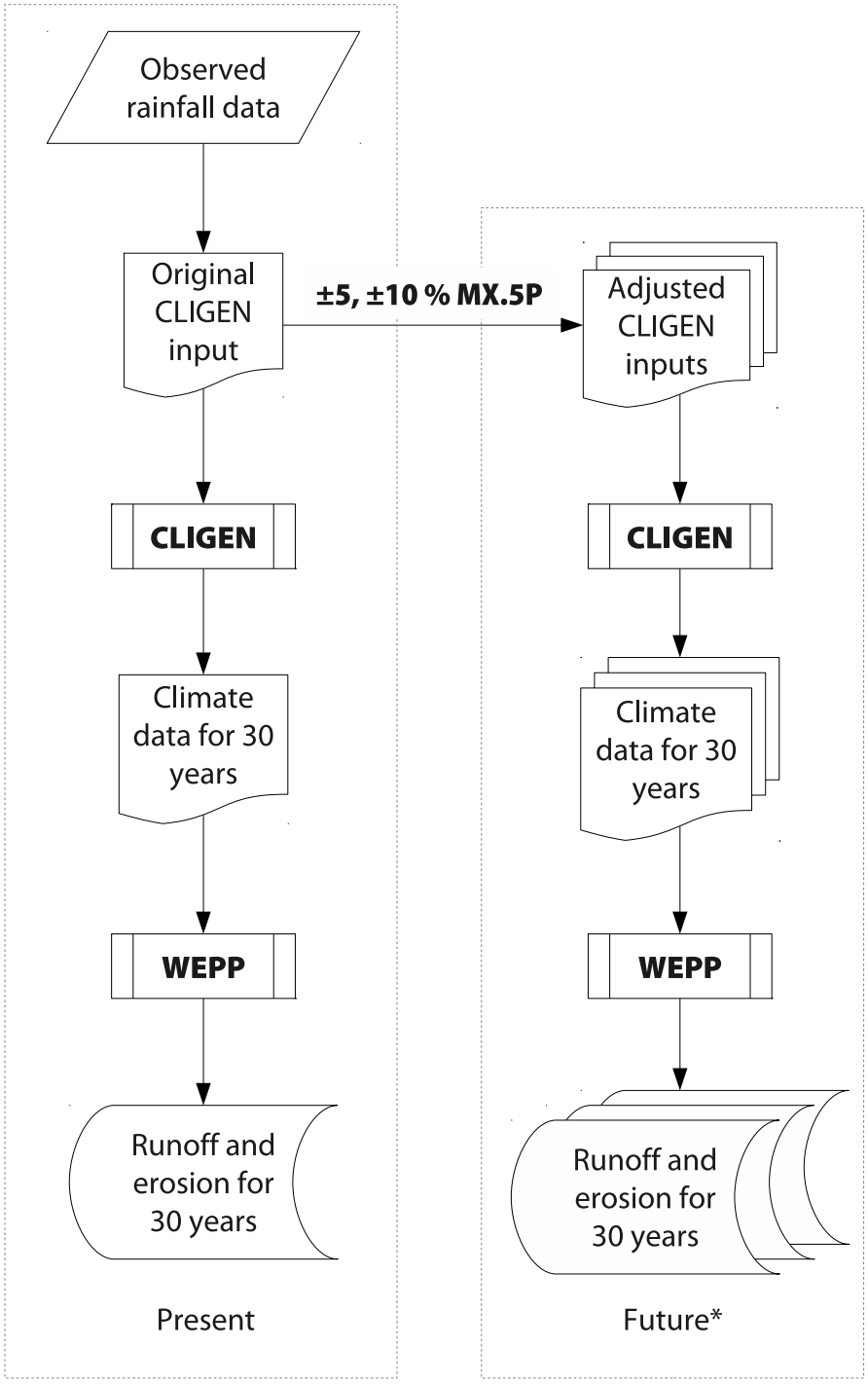


Figure 9.1 Schematic flowchart of the method which is used for investigation of implications of rainfall intensity changes for future soil erosion. Soil erosion simulated in the left-side box marked with 'Present' represents the present erosion rate under current rainfall intensity. Soil erosion simulated in the right-side box marked with 'Future*' represents assumed future erosion rates under the different rainfall intensities.

duration, D can be described as:

$$I = i_p \times \frac{R}{D} \tag{9.4}$$

where i_p is normalised peak intensity, R is rainfall amount.

The rainfall amount, R, and normalised peak intensity, i_p, are parametrised in a CLIGEN input file as station specific parameters (i.e. MEAN P and MX.5P), so that they should not be changed directly from a CLIGEN output file. On the other hand, rainfall duration, D, is generated by CLIGEN in relation to R and i_p values. Thus, *only* daily peak rainfall intensities are increased or decreased by decreasing or increasing rainfall duration while keeping the rainfall amount constant (Table 9.4). All other factors, such as rainfall frequency and seasonal intensity variation, are unchanged.

Table 9.4 Peak rainfall intensity changes (%) for WEPP simulation

Duration	142.9	125.0	111.1	100	90.9	83.3	76.9
Peak Intensity	70	80	90	100	110	120	130

Runoff and soil loss amount were estimated by WEPP (v2004.7). CLIGEN (v5.2) was used to generate weather data using updated Ditchling Road input (see Appendix B.2). Calibrated WEPP was used as previously reported. The resulting annual runoff and soil loss rate were analysed to find out whether WEPP is sensitive to rainfall intensity changes.

9.3.1 Runoff and Soil Loss

The mean annual soil loss estimated by WEPP increases or decreases as peak intensity increases or decreases (Figure 9.2). WEPP is sensitive to daily peak intensity changes with the rate of $\beta = 1.46$ ($y = \alpha + \beta x$). This means that for each 1% increase or decrease in daily peak intensity, WEPP estimates a 1.46% increase or decrease in the annual soil loss.

The annual runoff rate is slightly less sensitive to the changes in peak rainfall intensity than annual soil loss 9.2.

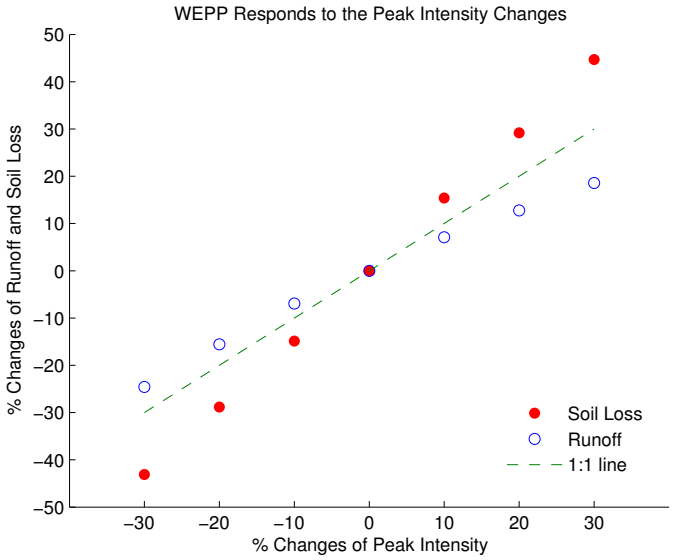


Figure 9.2 WEPP responses to the peak rainfall intensity changes

9.3.2 Discussion

As the result implies, WEPP is sensitive to a change in rainfall intensity.

Although the method used here is arguably simple and crude, it serves the aim of this study. It clearly shows the sensitivity of WEPP to rainfall intensity changes. However, the resultant change in rates of soil loss in response to the daily peak rainfall intensity is rather difficult to accept.

This is due to the following reasons:

- This is an indirect approach to changing rainfall intensity.
- The normalised daily peak intensity parameter, i_p, has not been changed. Thus, the relative magnitude of daily peak intensity to the daily average intensity is the same.

- No seasonal variation is considered as every rainfall duration is perturbed with the same change rate.

Moreover, when the same changes were applied to daily rainfall durations across the data period, some of the events became extended over 24 hour period. These events however were forced to be 24 hour events. This, however, did not affect the final results.

WEPP may be used for the investigation, *Estimation of Future Soil Erosion*. However, it is important to keep in mind the limitations discussed previously (see Section 7.7).

9.4 Estimation of Future Soil Erosion

As pointed out previously, our ability to predict future soil erosion is largely limited by the shortcomings of GCMs. At the time of writing, magnitudes of future rainfall intensity changes are not yet clearly quantified. Nevertheless, it is evident that the observed frequency of heavy rainfall has increased in the region of 2–4% over the latter half of the 20th century (IPCC Working Group I, 2001).

However, this still does not provide sufficient detail in rainfall information required by the soil erosion models used here. In this research, it has been shown that:

- temporal scales of rainfall data (WSIV)
- within-storm intensity pattern (WSIP)
- continuity of rainfall duration (WSP)

affect soil erosion, and it is vital to know these information in order to estimate soil erosion adequately. The effect of these factors on soil erosion are discussed previously (Chapter 5, Chapter 7 and Chapter 6).

In order to investigate the impacts of future rainfall intensity changes on soil erosion, it is undoubtedly necessary to know what future rainfall intensity is like, and then apply

these rainfall intensity changes to soil erosion models to estimate the future soil erosion rate. However, this seems rather problematic as pointed out previously. Also, the changes in rainfall intensity are geographically dependent, and thus is soil erosion.

Therefore, the important question is "What may change in relation to rainfall characteristics?" The following are expected to change:

- rainfall amount
- rainfall intensity
- rainfall (intensity) pattern
- number of wet and dry days (or ratio of wet/dry days)

In the future, we may experience a mixture of all these factors. However, with current technology for climate predictions, it is very difficult to quantify the changes in future rainfall characteristics with precise figures. In terms of rainfall intensity, it has been possible to speculate future rainfall intensity by looking at direct and indirect factors related to the rainfall intensity:

- Increased atmospheric moisture contents may lead to more frequent heavy rainfall events;
- Increased atmospheric water-holding capacity may lead to fewer raindays;
- Slight increase or almost no changes in future average rainfall amount.

The last point is a site specific factor for the research site considered in this thesis. By analysing observed daily rainfall amount data from the research site, South Downs, UK, it is evident that there is an increasing trend in daily rainfall intensity (i.e. SDII) with seasonal variabilities.

9.4.1 Estimated Future Rainfall for WEPP Simulations

A number of daily rainfall events generated by CLIGEN for all conditions are exactly the same. The number of raindays is about 151 days per year on average. The total annual rainfall amounts for all conditions are also the same (Figure 9.3).

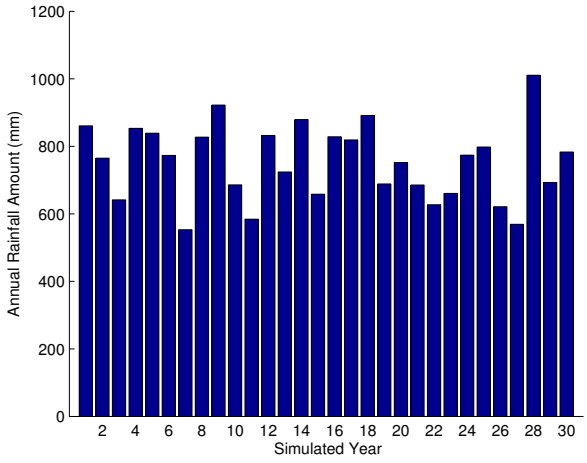


Figure 9.3 Simulated annual rainfall amount using CLIGEN

The changes in mean maximum 30-min peak intensity shows negative relationships, as expected, with the rainfall duration changes. Every 1% decrease/increase in mean maximum 30-min peak intensity of wet seasons results in a 0.75% increase/decrease in annual rainfall duration (Figure 9.4). For the changes in dry season, the magnitude of the change was more gradual than that of the wet season (Figure 9.4). Every 1% change in the peak intensity of dry season caused a −0.45% change in annual rainfall duration 9.4.

The changes in average monthly maxima of daily peak intensity for wet and dry season affected CLIGEN simulated daily peak rainfall intensities (Figure 9.5). The changes in average monthly maxima of daily peak intensity in the wet season resulted in increased or decreased daily peak intensities for wet months (SONDJF). This was also the case for the dry months (MAMJJA).

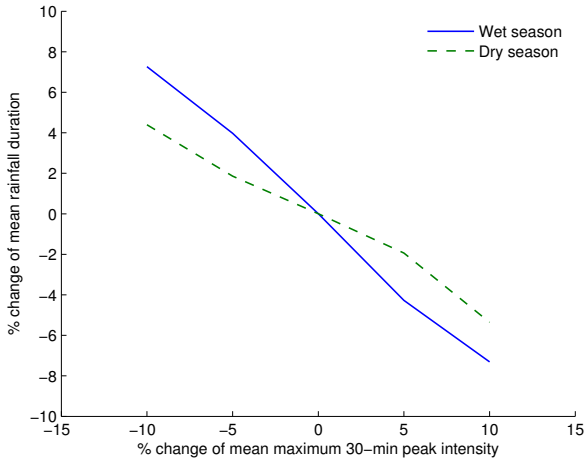


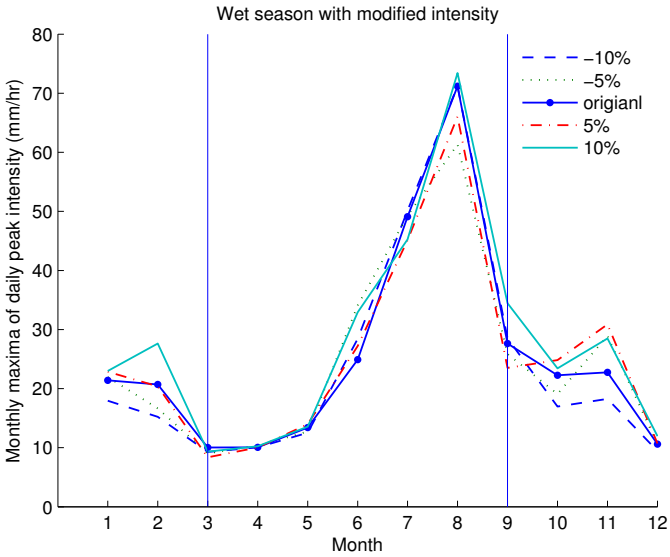
Figure 9.4 Simulated annual rainfall duration changes by changing mean maximum 30-min peak intensity for wet and dry seasons.

9.4.2 Estimated Changes of Future Soil Erosion

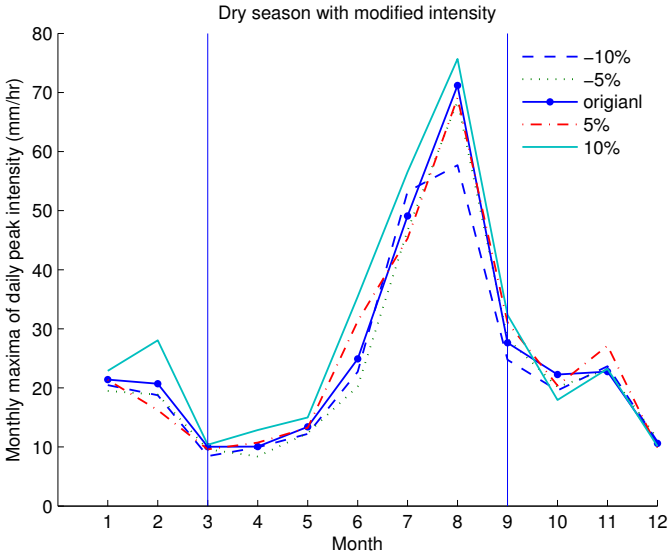
For the wet season, increases or decreases in mean maximum 30-min peak intensity generally yield increases or decreases in runoff. Every 1% change in the mean maximum 30-min peak intensity for the wet months (SONDJF) resulted in about a 0.72% change in the mean annual runoff (Figure 9.6). For the dry season, 5% change in mean maximum 30-min peak intensity yield the greatest changes in runoff (Figure 9.6) compared to 10% changes in the intensity. When mean maximum 30-min peak intensity increases ten per cent, runoff increases, but increases less than that of 5% change in the intensity. The similar effect is observed for 10% decrease in the intensity.

The effect of mean maximum 30-min peak intensity changes on soil loss changes are more distinctive than on runoff. The effect of the intensity changes in the wet season and the dry season are markedly different (Figure 9.7). For the wet season, every 1% increase or decrease in mean maximum 30-min peak intensity resulted in about a 2% increase or decrease in mean annual soil loss rates (Figure 9.7).

The change in mean maximum 30-min peak intensity for dry months show no



(a) Wet months (9, 10, 11, 12, 1, 2) with modified intensity



(b) Dry months (3, 4, 5, 6, 7, 8) with modified intensity

Figure 9.5 Monthly maxima of daily peak rainfall intensity changes generated by CLIGEN with modified mean maximum 30-min peak intensity

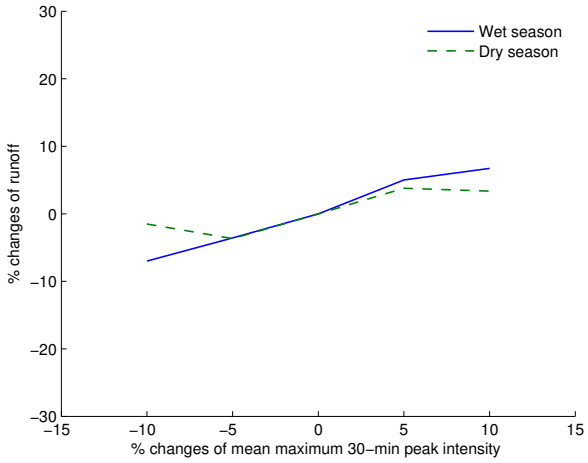


Figure 9.6 Runoff changes in response to the changes of mean maximum 30-min peak intensity for wet and dry seasons.

significant effect on soil loss rates except a 5% increase in the intensity (Figure 9.7). When mean maximum 30-min peak intensity is 5% increased, average annual soil loss rate increase about a 13.3% in the dry season (Figure 9.7). This is a 2.7% increase in soil loss rate per every 1% increase in the intensity. This rate of change is greater than the magnitude of the effect of the intensity changes in the wet season (i.e. a 2% change in soil loss per every 1% change in the intensity).

9.4.3 Discussion

The exceptional response of soil loss rate changes to the 5% increase in mean maximum 30-min peak intensity in the dry season are investigated by looking into event by event simulation results. The 5% increase in the intensity increases the number of storm runoff incidents than with original intensity. However, amount of runoff generated by 5% increased intensity is slightly (i.e. 4%) greater than that of the original intensity (mean runoff amount generated per event is 74.8 mm). This means that each 1% increase in the intensity resulted in a 0.8% increase in runoff. Despite this small differences in runoff amounts, soil loss rates are 13% increased in response to 5% increase in the intensity in

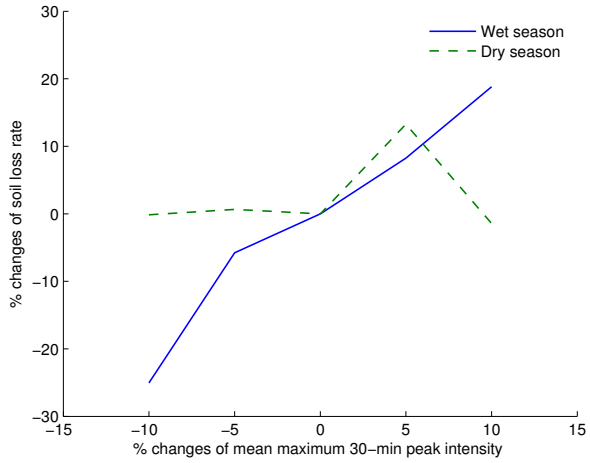
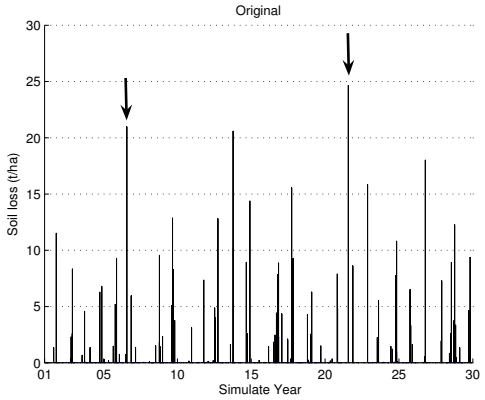


Figure 9.7 Soil loss rate changes in response to the changes of mean maximum 30-min peak intensity for wet and dry seasons.

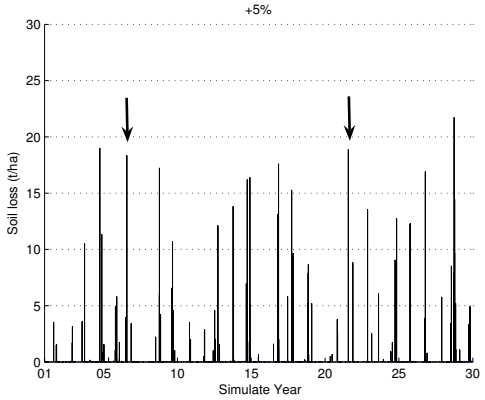
the dry season.

By looking at the number of events which yield soil loss rates more than 15 t/ha, there are 6, 10 and 8 events for the original intensity, 5% increased intensity and 10% increased intensity, respectively (Figure 9.8). There are evidently more incidents of large erosion events for 5% increased intensity. However, the differences in number of erosion event over 15 t/ha are not the result of intensity changes in the dry season. By looking at the date of each events, far from two events on 29 July in year 6 and in year 21, all other events occurred in the wet season, mostly in September, October and November. Also, 29 July is the same date as the harvest date used for WEPP management input (Table 3.5).

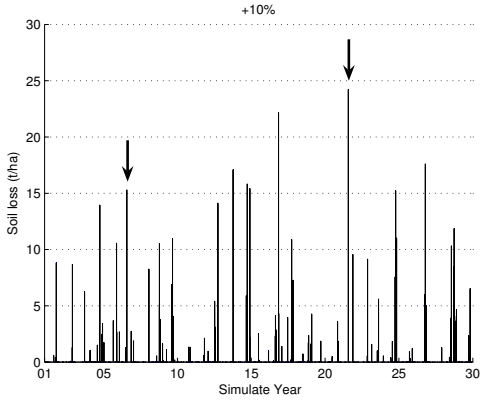
The intensity increase in dry months is not significant to cause a change in erosion rate as either they do not have sufficient rainfall amounts to initiate erosion or surface conditions are not susceptible for erosion because of sufficient crop covers. The rainfall intensity becomes more important where other factors such as rainfall amounts are enough to initiate soil erosion. Thus, intensity increases in the dry months are not effective as intensity increases in the wet months where rainfall amounts are greater.



(a) Original



(b) +5%



(c) +10%

Figure 9.8 Effects of 5% and 10% increases of mean maximum 30-min peak intensity on WEPP generated soil loss rates (t/ha) for individual events. The arrows indicate the erosion events with >15 t/ha soil loss on 29 July of year 6 and year 21.

The effect of an increase or decrease in monthly mean maximum 30-min peak intensity in the wet months (SONDJF) are not constrained only to the wet months, but also slightly to other months—i.e. the dry months (MAMJJA) decreasing or increasing the peak intensity (Figure 9.5a). A similar effect is also observed when monthly mean maximum 30-min peak intensity in the dry months are changed (Figure 9.5b). This may be due to the fact that CLIGEN attempts to keep the overall rainfall amount close to the original value.

Each percent change in a peak intensity of extreme events during the wet season may result in double percent changes in soil loss rates. This is partly due to WEPP estimates a gradual increase in runoff amount while the number of runoff events is reduced. As a result of an increased peak intensity during the wet season, less rainfall events were simulated to retain overall rainfall amount and number of raindays.

The WEPP simulation results in this chapter suggest that every 1% increase or decrease in the mean maximum 30-min peak intensity in the wet season (September to February) resulted in a 0.72% increase or decrease in mean annual runoff, and a 2% increase or decrease in mean annual soil loss rate.

We do not know precisely what the future rainfall intensity would be like. Even with climate change models, it is difficult to predict all the rainfall information required by the present-day erosion models. Without knowing these rainfall intensity, estimation of future erosion can go wrong easily as shown previously. However, using perturbed extreme rainfall intensity will provide a clear and robust comparisons of soil erosion rates under the conditions where the extreme rainfall intensity is expected to be increased or decreased.

Despite the availability of various methods we take to predict future rainfall intensity, predicting soil erosion with good confidence level is almost impossible (may not be

viable) at the moment because the uncertainty involved for the prediction is too great to be meaningful. As shown in this research, even with slight different rainfall intensity from the true value—which we may not be able to know truly—will result in completely different soil erosion results. However, it is true to say that increased rainfall which may mean—not necessarily always though—increased erosive power of rainfall and this increase will result in increased erosion rates.

9.5 Conclusion

This chapter aimed to find out the impact of rainfall intensity changes on future soil erosion by looking at the effect of increased and decreased extreme rainfall intensity. Two seasonal variations were considered—the wet and dry season.

The method employed in this chapter successfully generated two different climate datasets with perturbed monthly rainfall intensity without affecting rainfall amount and frequency of rainfall. It is important to acquire such dataset in order to investigate effect of rainfall intensity without compound effects from other rainfall factors such as amount and frequency of rainfall.

The WEPP simulation results in this chapter suggest that, where the mean maximum 30-min peak intensity in the wet months increases, runoff and soil erosion increase. Particularly the amount of erosion increases at a even greater rate than the amount of runoff. The ratio of erosion increases to the rainfall intensity increase is on the order of **2.**

All the figures of simulation outputs from this stage should not be accepted as "true" values without careful interpretations. They do not have an adequate certainty to be accepted directly. It should also be noted that high levels of uncertainty may be present in the result of the simulation.

Part IV

Conclusion

Chapter 10

CONCLUSION

The main objective of this research has been to investigate possible implications of climate change for future erosion with reference to rainfall intensity changes by analysing the response of erosion models to arbitrary rainfall intensity changes, and implicitly the process understanding on which the models are based. Thus, this research is a step towards the ultimate goal of predicting future rates of soil erosion caused by future rainfall intensity changes.

To achieve this aim, following four research questions have been tackled:

Question 1. What role does rainfall intensity play in the process descriptions which comprise erosion models?

Question 2. Assuming that we use a model to predict erosion rates under the future climate which may have different rainfall intensities from the present, what information do we need to make predictions in terms of both climate and process understanding?

Question 3. What do we know about future rainfall intensity? Does any trend exist in the present and past rainfall intensity at the study site? If so, is the trend consistent with future rainfall intensity predicted by climate models? If not, what must be done to estimate future rainfall intensity?

Question 4. Are we in a position to predict soil erosion under the future climate? If not, what must be done?

Findings with respect to each of these research questions are summarised below, along with limitations which have resulted from the approach used. This section finishes with some suggestions for future research.

10.1 Rainfall Intensity and Process Descriptions

10.1.1 Findings

There is a difference between the theoretical treatment of rainfall intensity in erosion models, and the practical handling of it. A first finding was that WSIV affects the results of simulations. Rainfall events with a constant intensity produced dramatically less erosion amounts compared with storms with the same total volume of rainfall, but increasing or decreasing intensity. This a constant intensity is not a good representation of rainfall intensity for a natural rainfall event as far as erosion modelling is concerned.

In addition, it appears that a higher temporal resolution is needed for rainfall data that have high within-storm intensity variations. WSIP have a larger effect on estimations of soil erosion compared with runoff. Thus, the temporal resolution of rainfall data affects the results of erosion simulations. As the temporal resolution of rainfall increased, then the amounts of estimated soil loss also increased. Thus a study which uses rainfall data with different temporal resolutions will give rise to artefacts i.e.

changes in estimated soil loss may be due only to the different temporal resolutions of rainfall.

In addition, WSP (Within-Storm Pause) also have a marked effect on erosion estimations. Discontinuous storms (i.e. with within-storm gaps) would be expected to produce less runoff and soil loss than an equivalent continuous storm (i.e. a storm with the same total rainfall, but with WSPs removed), since the longer duration of the discontinuous storm gives rise to a lower average intensity for the storm, compared with the continuous storm. However, an unexpected result from WEPP was that more soil loss was estimated with discontinuous rainfall than with volume-equivalent continuous rainfall. This suggests a design flaw in the rainfall data description used in WEPP, due to WEPP's handling of the original breakpoint data (it is internally reconstructed to "WEPP-interpreted" data, and this "reconstructed" data is used in the simulations. Limitations here mean that some information is lost when the reconstructed data is compared to the original breakpoint data.)

10.1.2 Limitations

All data used here was for only one site (i.e. Woodingdean, South Downs, UK). Thus, there is a chance that the erosion models may give different results when other slope data are used.

No comparisons of estimated runoff and erosion rates against measured runoff and erosion rates were possible because of the absence of observed data for the individual events considered. However, the changes in runoff and erosion rates from laboratory experiments with similar storm intensity conditions show similar runoff and erosional responses to the intensity changes. Proper comparisons of soil erosion can only be made when there is observed erosion rates, which then can be used as a reference. The validity of the results thus need to be supported by a different approach.

10.2 What do we need to predict erosion under future changed rainfall intensities?

10.2.1 Findings

Temporal resolution of rainfall data affect results of erosion simulations. As temporal resolutions increase, amounts of erosion estimations increase. Using rainfall data with an inconsistent temporal resolution for erosion simulations may result in erroneous erosion estimations. Higher temporal scale is needed when rainfall data that have high WSIV (Within-Storm Intensity Variation) are used for erosion estimations.

WSIP (Within-Storm Intensity Pattern) have an effect on estimations of soil erosion. WSIPs have more effects on soil loss than runoff. Rainfall events with a constant intensity produced dramatically less erosion amounts than other WSIPs such as increasing or decreasing. Constant intensity is not a good representation of rainfall intensity for a natural rainfall event as far as erosion modelling is concerned.

Within-Storm Pauses (WSPs) have an effect on erosion estimations. Discontinuous rainfall events (i.e. WSPs included) were expected to produce less runoff and soil loss than continuous rainfall events (i.e. WSPs removed) that has the same rainfall amount as discontinuous events. This is because relatively longer rainfall durations of discontinuous rainfall events imply that the events have relatively less intense intensity than continuous events. However, unexpected results from WEPP simulations found that WEPP estimates more soil loss with discontinuous rainfall than with continuous rainfall. This revealed a design flaw in the rainfall data description used in WEPP. WEPP modifies original intensity information of breakpoint data by reconstructing the data to "WEPP-interpreted" data, and uses this "reconstructed" data for simulations of erosion.

To predict future soil erosion that has been affected by future rainfall intensity changes, the following are required:

1. Long-term rainfall data with adequately high temporal resolution, high enough to capture details of Within-Storm Intensity Variations (WSIVs)
2. Information about Within-Storm Intensity Patterns (WSIPs)
3. Duration and frequency of Within-Storm Pauses (WSPs) within a storm
4. An erosion model that can make proper use of rainfall intensity information stated above (e.g. using data with up to 1440 breakpoints, at least)
5. An erosion model that can simulate long-term soil erosion continuously—a continuous simulation model.

To predict future soil erosion that has been affected by future rainfall intensity changes, the following are required:

1. Long-term rainfall data with adequately high temporal resolution, high enough to capture details of within-storm intensity variations
2. Information about the duration and frequency of no-rain periods within a storm
3. An erosion model that can make proper use of this rainfall intensity information i.e. which does not simply the breakpoint data as does WEPP.
4. An erosion model that can simulate long-term soil erosion continuously—a continuous simulation model

10.2.2 Limitations

Long term trends of rainfall intensity at the study site were only available at daily scale. These daily trends cannot be used with the erosion models directly. Sub-daily rainfall data are required for modelling erosion. Slope data used for erosion simulations are obtained from one site (i.e. Woodingdean, South Downs, UK). Thus, there is a chance that the erosion models may give different results when other slope data are used.

No comparisons of estimated runoff and erosion rates against measured runoff and erosion rates were possible because of the absence of observed data for the individual events considered. However, the changes in runoff and erosion rates from laboratory experiments with similar storm intensity conditions show similar runoff and erosional responses to the intensity changes. Proper comparisons of soil erosion can only be made when there are observed erosion rates, which then can be used as a reference. The validity of the results thus need to be examined using a different approach.

10.3 Past and Present Rates of Rainfall Intensity

10.3.1 Findings

No significant trend of rainfall intensity have been found at the research site with the analysis of multi-scaled rainfall datasets. However, decreasing tendencies of rainfall amounts in July and March were observed from some stations. Also, declining number of wet-days per year were noted. With little or no change in rainfall amounts, these imply subtle increases in daily rainfall intensity may be expected. Availability of long-term high-resolution rainfall records is paramount for investigations into trends in rainfall intensity at an appropriate scale for erosion modelling. Future scenarios of intensity change were constructed for use in the erosion simulations (Chapter 9).

10.3.2 Limitations

Rainfall trends from the observed rainfall data are site- and time-specific. The other data such as soil and slope data used for estimations were obtained from one area (Figure 3.3), and collected for a certain time period. Although long-term (i.e. 10–99 years) observed rainfall data were used for the intensity trend investigations, high-resolution data—which are required for intensity analysis and the erosion simulation—were available only for relatively short periods (i.e. 2–13 years) with missing data periods (See Table 3.1 and 3.2).

10.4 Can we predict erosion rates under future changed rainfall intensities?

10.4.1 Findings

The WEPP simulation results suggest that, where mean maximum 30-min peak intensity of the wet months increases, runoff and erosion increase. Particularly the amount of erosion increases at a even greater rate than the amount of runoff: i.e. erosion is more sensitive to increased rainfall intensity, compared with runoff.

10.4.2 Limitations

This research is mainly based on computerised model simulations. Thus, the results from the research should not be confused with real observation. The models merely try to simulate the real soil erosion, based on the known statistical relationships between processes involved in soil erosion.

10.5 Suggestions for Future Research

The conclusion of this research does not suggest the dismissal of the use of erosion models for the study on future erosion, but instead it points out that there are some crucial aspects, which have been identified during the course of the research, and that they need to be satisfied in order to heighten our ability to estimate future erosion.

The reatest realisation this research has made is that there are still lots of questions waiting to be answered in the area of modelling erosion by water, particularly in relation to future rainfall intensity.

A number of future research topics can be suggested.

1. Experiments/measurements of duration/frequency of Within-Storm Pauses (WSPs) and their implications for soil erosion
2. Experiments/measurements of Within-Storm Intensity Patterns (WSIPs) and their implications for soil erosion
3. Experiments/measurements of Within-Storm Intensity Variations (WSIVs) and their implications for soil erosion
4. Developments of erosion models that can make appropriate use of the information on WSIPs, WSIVs and WSPs
5. Investigations/predictions of the future trends of WSIPs, WSIVs and WSPs

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Appendices

Appendix A

WEPP Input Data

A.1 Weather Input Data

A.1.1 For Temporal Scale Simulation

A.1.1.1 4 July 2000, Plumpton—CLIGEN

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)               (C)   (C) (l/d) (m/s)(Deg)   (C)

1-min:
  4  7 2000  74.8  5.2  0.63   4.20   6.7   3.3  98.  3.4  103.   0.8

5-min:
  4  7 2000  74.8  11.1  0.58   6.41   6.7   3.3  98.  3.4  103.   0.8

15-min:
  4  7 2000  74.8  13.3  0.54   3.69   6.7   3.3  98.  3.4  103.   0.8

30-min:
  4  7 2000  74.8  14.0  0.52   2.95   6.7   3.3  98.  3.4  103.   0.8

60-min:
  4  7 2000  74.8  14.0  0.54   2.65   6.7   3.3  98.  3.4  103.   0.8
```

A.1.1.2 4 July 2000, Plumpton—Breakpoint

```
5.22564
```

```
   2   0   0
 Station:  Plumpton                                      CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
    day  mon  year  nbrkpt  tmax   tmin   rad    vwind   wind   tdpt
                             (C)    (C)  (l/d)   (m/s)   (deg)   (C)
15-min:
     4    7   2000    55     6.7    3.3    98.    3.4   103.    0.8
00.00    0
00.15    0.2
00.30    1
00.45    1.8
01.00    2.6
01.15    3.6
01.30    4.6
01.45    4.8
02.00    5.4
02.15    6.4
02.30    7.4
02.45    8.6
03.00    10
03.15    11.2
03.30    12.6
03.45    14
04.00    15
04.15    16
04.30    17
04.45    17.4
05.00    18
05.15    18.4
05.30    19
05.45    22.2
06.00    26.2
06.15    30
06.30    33.6
06.45    34.6
07.00    37.4
07.15    42.6
07.30    44.6
07.45    48.8
08.00    52.2
08.15    54
08.30    56.2
08.45    59.8
09.00    64.8
09.15    66.6
09.30    68.2
09.45    68.8
10.00    69.6
10.15    70.2
10.30    71.2
10.45    72.2
11.00    72.4
11.30    72.8
11.45    73
12.00    73.4
12.15    73.6
12.30    73.8
12.45    74.2
```

```
13.15    74.4
13.30    74.6
13.45    74.8
14.00    74.8

30-min:
     4    7   2000     30    6.7    3.3    98.    3.4   103.    0.8
00.00    0
00.30    0.2
01.00    1.8
01.30    3.6
02.00    4.8
02.30    6.4
03.00    8.6
03.30    11.2
04.00    14
04.30    16
05.00    17.4
05.30    18.4
06.00    22.2
06.30    30
07.00    34.6
07.30    42.6
08.00    48.8
08.30    54
09.00    59.8
09.30    66.6
10.00    68.8
10.30    70.2
11.00    72.2
11.30    72.4
12.00    73
12.30    73.6
13.00    74.2
13.30    74.4
14.00    74.8
14.30    74.8

60-min:
     4    7   2000    16     6.7    3.3    98.    3.4   103.    0.8
00.00    0
01.00    1.8
02.00    4.8
03.00    8.6
04.00    14
05.00    17.4
06.00    22.2
07.00    34.6
08.00    48.8
09.00    59.8
10.00    68.8
11.00    72.2
12.00    73
13.00    74.2
14.00    74.8
15.00    74.8
```

A.1.1.3 11 October 2000, Plumpton—CLIGEN

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
```

```
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)               (C)   (C) (l/d) (m/s)(Deg)   (C)
1-min:
 11 10 2000 133.8  7.40 0.12   4.64   6.7   3.3  98.  3.4  103.   0.8

5-min:
 11 10 2000 133.8 12.80 0.46   5.53   6.7   3.3  98.  3.4  103.   0.8

15-min:
 11 10 2000 133.8 15.50 0.49   2.87   6.7   3.3  98.  3.4  103.   0.8

30-min:
 11 10 2000 133.8 17.00 0.93   2.69   6.7   3.3  98.  3.4  103.   0.8

60-min:
 11 10 2000 133.8 18.00 0.64   2.23   6.7   3.3  98.  3.4  103.   0.8
```

A.1.1.4 11 October 2000, Plumpton—Breakpoint

```
5.22564
   2   1   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
    day  mon  year  nbrkpt  tmax   tmin   rad    vwind   wind   tdpt
                             (C)    (C)  (l/d)   (m/s)   (deg)   (C)
15-min:
    11   10   2000    63     6.7    3.3    98.    3.4   103.    0.8
00.00    0
00.15    0.8
00.30    1.2
00.45    1.2
01.15    1.6
01.30    1.6
05.15    1.8
05.45    4
06.00    8.2
06.15    8.8
06.30    11.2
06.45    12.8
07.00    13.8
07.15    18
07.30    18
07.45    19.4
08.00    19.8
08.15    20.6
08.30    21
08.45    25.4
09.00    25.6
09.15    25.6
```

```
09.30    29.8
09.45    33.4
10.00    36.4
10.15    38.2
10.30    39.8
11.00    42.8
11.15    43.2
11.30    44.2
11.45    48.8
12.00    49
12.15    49.6
12.30    55.8
12.45    58.8
13.00    60.6
13.30    64.4
13.45    69
14.00    74.4
14.15    79
14.30    82.6
14.45    85.4
15.00    88.4
15.15    90
15.30    91
15.45    92.8
16.00    95.2
16.15    99.6
16.30    101.8
16.45    104.2
17.00    107.8
17.15    108.2
17.30    109
17.45    110.8
18.00    111.2
18.15    114.4
18.30    115.8
18.45    119
19.00    123.4
19.15    129.6
19.30    133
19.45    133.2
20.15    133.8

30-min:
    11   10   2000    35     6.7    3.3    98.    3.4   103.    0.8
00.00    0
00.30    0.8
01.00    1.2
02.00    1.6
05.30    1.8
06.00    4
06.30    8.8
07.00    12.8
07.30    18
08.00    19.4
08.30    20.6
09.00    25.4
09.30    25.6
10.00    33.4
10.30    38.2
11.00    41.4
11.30    43.2
12.00    48.8
12.30    49.6
13.00    58.8
13.30    62.4
14.00    69
14.30    79
```

```
15.00    85.4
15.30    90
16.00    92.8
16.30    99.6
17.00    104.2
17.30    108.2
18.00    110.8
18.30    114.4
19.00    119
19.30    129.6
20.00    133.2
20.30    133.8

60-min:
    11   10   2000    19     6.7    3.3    98.    3.4   103.    0.8
00.00    0
02.00    1.6
03.00    1.6
06.00    1.8
07.00    8.8
08.00    18
09.00    20.6
10.00    25.6
11.00    38.2
12.00    43.2
13.00    49.6
14.00    62.4
15.00    79
16.00    90
17.00    99.6
18.00    108.2
19.00    114.4
20.00    129.6
21.00    133.8
```

A.1.2 For Storm Patterns Simulation

A.1.2.1 Constant Intensity—20 mm/hr

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)               (C)   (C) (l/d) (m/s)(Deg)   (C)
  1  1 2000  120.0  12.0  1.0   1.00   6.7   3.3  98.  3.4  103.   0.8
```

A.1.2.2 Increasing Intensity—20 mm/hr

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
```

```
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)              (C)   (C) (l/d) (m/s)(Deg)   (C)
  1  1 2000  120.0  12.0  0.99   2.00   6.7   3.3  98.  3.4  103.   0.8
```

A.1.2.3 Decreasing Intensity—20 mm/hr

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)              (C)   (C) (l/d) (m/s)(Deg)   (C)
  1  1 2000  120.0  12.0  0.01   2.00   6.7   3.3  98.  3.4  103.   0.8
```

A.1.2.4 Increasing-Decreasing Intensity—20 mm/hr

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)              (C)   (C) (l/d) (m/s)(Deg)   (C)
  1  1 2000  120.0  12.0  0.5   2.00   6.7   3.3  98.  3.4  103.   0.8
```

A.1.2.5 Constant Intensity—60 mm/hr

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
```

```
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)              (C)   (C) (l/d) (m/s)(Deg)   (C)
  1  1 2000  120.0  2.0  1.0   1.00   6.7   3.3  98.  3.4  103.   0.8
```

A.1.2.6 Increasing Intensity—60 mm/hr

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)              (C)   (C) (l/d) (m/s)(Deg)   (C)
  1  1 2000  120.0  2.0  0.99   2.00   6.7   3.3  98.  3.4  103.   0.8
```

A.1.2.7 Decreasing Intensity—60 mm/hr

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)              (C)   (C) (l/d) (m/s)(Deg)   (C)
  1  1 2000  120.0  2.0  0.01   2.00   6.7   3.3  98.  3.4  103.   0.8
```

A.1.2.8 Increasing-Decreasing Intensity—60 mm/hr

```
5.22564
   2   0   0
  Station:  Plumpton                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
```

```
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
 da mo year  prcp  dur   tp     ip  tmax  tmin  rad  w-vl w-dir  tdew
             (mm)  (h)              (C)   (C) (l/d) (m/s)(Deg)   (C)
  1  1 2000  120.0  2.0  0.5   2.00   6.7   3.3  98.  3.4  103.   0.8
```

A.1.3 For Continuous and Discontinuous Rainfall Simulation

A.1.3.1 Continuous

```
5.22564
   2   1   0
  Station:  Southover                                      CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
    day  mon  year  nbrkpt  tmax   tmin   rad    vwind   wind   tdpt
                             (C)    (C)  (l/d)   (m/s)   (deg)   (C)
    11   10   2000    59     6.7    3.3    98.    3.4   103.    0.8
00.00    0
00.15    0.8
00.30    2.6
00.45    3
01.00    4.2
01.15    4.4
01.30    4.6
01.45    5.2
02.00    6.2
02.15    6.4
02.30    7.4
02.45    9
03.00    9.4
03.15    12
03.30    14.6
03.45    17
04.00    18.2
04.15    18.4
04.30    19.4
04.45    21.4
05.00    22.4
05.15    23
05.30    26.2
05.45    29.6
06.00    30.2
06.15    31.4
06.30    31.8
06.45    33.4
07.00    41.6
07.15    45.4
07.30    46
07.45    49
08.00    50.8
08.15    52.6
08.30    54.8
08.45    56
09.00    57.2
```

```
09.15    57.8
09.30    60.2
09.45    61.6
10.00    63.6
10.15    64.6
10.30    67.8
10.45    71.2
11.00    73.2
11.15    75.2
11.30    77
11.45    79.8
12.00    80.4
12.15    82.8
12.30    84
12.45    84.2
13.00    84.6
13.15    85.2
13.30    86.2
13.45    86.6
14.00    88.2
14.15    89
14.30    89.8
```

A.1.3.2 Discontinuous

```
5.22564
   2   1   0
  Station:  Southover                                    CLIGEN VER. 5.22564 -r:    0 -I: 0
 Latitude Longitude Elevation (m) Obs. Years   Beginning year  Years simulated Command Line:
    51.00     0.13          32           9        1991              -1
 Observed monthly ave max temperature (C)
   6.3   6.1   8.3  11.4  14.6  17.7  19.7  19.6  17.2  13.9  10.0   8.0
 Observed monthly ave min temperature (C)
   1.3   1.1   2.7   4.4   7.5  10.6  12.7  12.8  10.9   8.2   4.9   3.4
 Observed monthly ave solar radiation (Langleys/day)
  81.0 137.0 234.0 399.0 483.0 530.0 518.0 465.0 312.0 187.0 101.0  66.0
 Observed monthly ave precipitation (mm)
  42.0  31.9  71.9  57.0  53.9  38.7  41.4  33.6  78.8 102.2  71.3 109.3
    day  mon  year  nbrkpt  tmax   tmin   rad    vwind   wind   tdpt
                             (C)    (C)  (l/d)   (m/s)   (deg)   (C)
    11   10   2000    59     6.7    3.3    98.    3.4   103.    0.8
00.00    0
00.15    0.8
01.15    2.6
01.30    3
01.45    4.2
02.00    4.4
03.30    4.6
04.00    5.2
05.30    6.2
05.45    6.4
06.15    7.4
07.15    9
07.30    9.4
07.45    12
08.00    14.6
08.45    17
09.00    18.2
09.15    18.4
09.45    19.4
10.00    21.4
10.15    22.4
10.30    23
10.45    26.2
11.00    29.6
```

```
11.15    30.2
11.30    31.4
11.45    31.8
12.00    33.4
12.15    41.6
12.30    45.4
12.45    46
13.00    49
13.15    50.8
13.30    52.6
13.45    54.8
14.00    56
14.15    57.2
14.30    57.8
14.45    60.2
15.00    61.6
15.15    63.6
15.30    64.6
15.45    67.8
16.00    71.2
16.15    73.2
16.30    75.2
16.45    77
17.00    79.8
17.15    80.4
17.30    82.8
17.45    84
18.00    84.2
18.45    84.6
19.00    85.2
19.15    86.2
19.30    86.6
19.45    88.2
20.00    89
20.15    89.8
```

A.2 Soil Input—calibrated

```
2004.7
#
#   Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
#
Andover silt-loam soil
1       1
'Andover'  'silt loam'  4     30.0       1.0     2000000     0.0050  6.0     3.00
 150    18.9    3.5     7.0     45.     38.1
 200    18.9    3.5     4.8     39.     50.0
 300    25.0    24.0    2.2     30.     90.0
1000    25.0    24.0    1.2     14.     90.0
```

A.3 Management Input

```
2004.7
#
# Created on 9Sep95 by 'wman', (Ver. 15Apr95)
# Author: DFM
#       Adapted by Mintae Choi for DPhil thesis
#
1 # number of OFEs
100 # (total) years in simulation
```

```
#################
# Plant Section #
#################
1 # looper; number of Plant scenarios
#
# Plant scenario 1 of 1
#
JPWHEAT
'Winter wheat, UK: high fertilization level'
(from WEPP distribution database,
modified by DFM for UK conditions)
1 # 'landuse' - <Cropland>
mtons/hectare
5.2 3 23 0 6.4 35 0 0.152 1 0.0064
0.8 1 0.65 0.99 3 1970 0.48 0.9
2 # 'mfo' - <Non-fragile>
0.0085 0.0085 15 0 0.005 1.0 0.25 0 14 0
0 9 0
####################
# Operation Section #
####################
3 # looper; number of Operation scenarios
#
# Operation scenario 1 of 3
#
CHISSTSP
'Chisel plow, straight with spike pts'
(from WEPP distribution database)
1 # 'landuse' - <Cropland>
0.5 0.3 0
4 # 'pcode' - <Other>
0.05 0.3 0.5 0.3 0.023 1 0.15
#
# Operation scenario 2 of 3
#
HASP
'Harrow-spike tooth'
(from WEPP distribution database)
1 # 'landuse' - <Cropland>
0.3 0.2 0
4 # 'pcode' - <Other>
0.025 0.05 0.3 0.2 0.015 1 0.025
#
# Operation scenario 3 of 3
#
UKROLL
'Roller (modified DFM)'
1 # 'landuse' - <Cropland>
0.1 0.1 0
4 # 'pcode' - <Other>
0.01 0.075 0.1 0.1 0.01 1 0
##############################
# Initial Conditions Section #
##############################
1 # looper; number of Initial Conditions scenarios
#
# Initial Conditions scenario 1 of 1
#
WHEATCNV
Conventional winter wheat cultivation
1 # 'landuse' - <Cropland>
1.2 0.3 91 124 0 0.1
1 # 'iresd' - <WIWHEAT1>
1 # 'mgmt' - <Annual>
250 0.01 0.1 0.043 0
1 # 'rtyp' - <Temporary>
0 0 0.1 0.2 0
```

```
0 0
############################
# Surface Effects Section #
############################
1 # looper; number of Surface Effects scenarios
#
# Surface Effects scenario 1 of 1
#
WHEATCNV
Conventionally-tilled winter wheat
1 # 'landuse' - <Cropland>
3 # 'ntill' - <number of operations>
232 # 'mdate' - <8 /20>
1 # 'op' - <CHISSTSP>
0.25
1 # 'typtil' - <Primary>
258 # 'mdate' - <9 /15>
2 # 'op' - <HASP>
0.05
2 # 'typtil' - <Secondary>
274 # 'mdate' - <10/1 >
3 # 'op' - <ROLLER04>
0.01
2 # 'typtil' - <Secondary>
######################
# Contouring Section #
######################
0 # looper; number of Contouring scenarios
####################
# Drainage Section #
####################
0 # looper; number of Drainage scenarios
##################
# Yearly Section #
##################
1 # looper; number of Yearly scenarios
#
# Yearly scenario 1 of 1
#
WHEATCNV
Conventionally-tilled winter wheat
1 # 'landuse' - <Cropland>
1 # 'itype' - <WIWHEAT1>
1 # 'tilseq' - <WHEATCNV>
0 # 'conset' - <NotUsed>
0 # 'drset' - <NotUsed>
1 # 'mgmt' - <Annual>
210 # 'jdharv' - <7 /29>
271 # 'jdplt' - <9 /28>
0.1
6 # 'resmgmt' - <None>
######################
# Management Section #
######################
WHEATCNV
Woodingdean continuous winter wheat
For NATO-ARW paper
DFM 7 Nov 1995
1 # 'nofe' - <number of Overland Flow Elements>
1 # 'Initial Conditions indx' - <WHEATCNV>
100 # 'nrots' - <rotation repeats..>
1 # 'nyears' - <years in rotation>
#
# Rotation 1 : year 1 to 1
#
1 # 'nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
1 # 'YEAR indx' - <WHEATCNV>
```

```
#
# Rotation 2 : year 2 to 2
#
1 # 'nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
1 # 'YEAR indx' - <WHEATCNV>
#
# Rotation 3 : year 3 to 3
#
1 # 'nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
1 # 'YEAR indx' - <WHEATCNV>
#
# Rotation 4 : year 4 to 4
#
1 # 'nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
1 # 'YEAR indx' - <WHEATCNV>
#
# Rotation 5 : year 5 to 5
#
1 # 'nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
1 # 'YEAR indx' - <WHEATCNV>

                  ###################################
                  # ... repeated upto 100 years ... #
                  ###################################

# Rotation 100 : year 100 to 100
#
1 # 'nycrop' - <plants/yr; Year of Rotation :  1 - OFE : 1>
1 # 'YEAR indx' - <WHEATCNV>
```

A.4 slope Input

Slope D

```
2004.7
#
#   Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
1
305     50
3       135
0.0 0.14 0.9 0.14 1.0 0.01
```

Slope E

```
2004.7
#
#       Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
#
1
305     50
4       150
0.0 0.12 0.5 0.15 0.9 0.12 1.0 0.01
```

Slope F

```
2004.7
#
```

```
#       Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
#
1
305     50
4       165
0.0 0.15 0.4 0.22 0.9 0.15 1.0 0.01
```

Slope G

```
2004.7
#
#       Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
#
1
305     50
4       180
0.0 0.17 0.35 0.25 0.9 0.17 1.0 0.01
```

Slope H

```
2004.7
#
#       Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
#
1
305     50
4       180
0.0 0.20 0.35 0.25 0.9 0.20 1.0 0.01
```

Slope I

```
2004.7
#
#       Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
#
1
305     50
4       165
0.0 0.19 0.4 0.27 0.9 0.19 1.0 0.01
```

Slope J

```
2004.7
#
#       Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
#
1
305     50
4       150
0.0 0.19 0.5 0.25 0.9 0.19 1.0 0.01
```

Slope K

```
2004.7
#
#       Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
#
1
305     50
4       140
0.0 0.18 0.5 0.19 0.9 0.18 1.0 0.01
```

Slope L

```
2004.7
#
#       Created by DFM on 9 Sep 95
#   Adapted by Mintae Choi for DPhil thesis
#
1
305     50
4       125
0.0 0.18 0.5 0.19 0.9 0.18 1.0 0.01
```

Appendix B

CLIGEN Input Data

B.1 Original Input for Ditchling Road

```
DITCHLING ROAD UK                        915000 0
LATT=  51.00 LONG=   0.13 YEARS= 15. TYPE= 1
ELEVATION =  105. TP5 = 4.29 TP6= 6.00
MEAN~P    0.19  0.16  0.17  0.16  0.16  0.20  0.19  0.22  0.23  0.27  0.21  0.20
S DEV P   0.21  0.17  0.18  0.19  0.17  0.23  0.28  0.28  0.27  0.34  0.27  0.23
SQEW  P   1.92  1.54  1.54  2.94  2.17  2.62  3.94  2.23  2.09  2.50  1.73  1.91
P(W/W)    0.66  0.71  0.65  0.62  0.60  0.57  0.53  0.53  0.63  0.63  0.66  0.63
P(W/D)    0.32  0.20  0.36  0.21  0.27  0.22  0.23  0.23  0.28  0.30  0.33  0.34
TMAX AV  43.29 43.00 46.99 52.59 58.32 63.82 67.44 67.19 63.01 57.02 50.07 46.38
TMIN AV  34.38 33.96 36.86 39.96 45.45 51.17 54.84 54.97 51.69 46.81 40.77 38.14
SD TMAX   5.76  5.52  4.18  6.11  6.32  6.65  6.08  5.14  4.17  4.48  5.24  4.71
SD TMIN   6.63  6.02  4.95  6.06  4.70  4.50  4.00  3.98  4.65  5.39  6.64 17.96
SOL.RAD    81.  137.  234.  399.  483.  530.  518.  465.  312.  187.  101.   66.
SD SOL    16.4  17.0  22.1  31.8  38.8  37.6  39.4  31.8  21.5  11.8  15.8  17.6
MX .5 P   0.63  0.59  0.55  0.55  0.55  0.55  0.55  0.67  0.79  0.93  0.87  0.75
DEW PT   35.21 34.76 36.71 38.45 43.04 47.32 50.04 50.06 49.20 44.50 39.94 37.49
Time Pk  0.185 0.261 0.351 0.439 0.509 0.588 0.649 0.725 0.800 0.869 0.926 1.000
% N       5.02  2.85  1.71  3.82  2.17  1.40  0.62  0.41  1.26  2.23  3.26  5.04
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.16  1.86  1.79  1.67  1.65  1.68  1.20  1.60  1.47  1.88  1.95  1.89
SKEW      0.22  0.28  0.16  0.18  0.01  0.30 -0.08 -0.01  0.65  0.23  0.41  0.31
% NNE     5.92  8.19  6.04  8.17  6.13  4.75  1.83  2.06  3.28  5.42  5.20  7.69
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.04  2.10  1.83  1.77  2.03  1.74  1.75  2.00  1.91  1.83  2.10  1.97
SKEW     -0.01 -0.01 -0.06  0.05  0.09 -0.07  0.32 -0.02  0.02  0.10  0.15  0.11
% NE     16.39 17.41 20.24 17.13 16.02 10.45  7.49  7.34  9.60 11.66 14.72 16.32
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.97  2.14  1.82  1.71  1.96  1.92  1.93  1.91  1.86  1.85  2.15  1.92
SKEW     -0.14  0.13 -0.05  0.22  0.21  0.14  0.28 -0.05 -0.03  0.22  0.23 -0.05
% ENE    27.65 30.14 34.63 27.20 26.30 21.39 20.20 18.94 21.34 22.85 25.11 25.31
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.85  1.88  1.77  1.76  1.70  1.77  1.82  1.67  1.71  1.72  1.83  1.91
SKEW      0.06 -0.01  0.12  0.12  0.10 -0.13  0.15  0.08  0.09  0.17  0.22 -0.13
% E      24.64 28.68 29.12 28.99 26.83 33.93 36.80 37.28 35.21 30.74 25.13 24.26
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.95  2.00  1.84  1.84  1.78  1.84  1.87  1.84  1.97  1.94  1.97  2.04
SKEW      0.05  0.00  0.31  0.13  0.05 -0.02  0.04 -0.12  0.03  0.11  0.18 -0.04
% ESE     7.82  6.08  4.62  9.71 13.47 18.20 23.12 27.05 21.47 16.84 12.72  7.87
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.96  1.60  1.88  1.86  2.04  1.88  1.83  1.88  1.85  1.88  1.96  1.97
SKEW      0.02  0.07  0.51  0.11  0.16  0.07  0.10 -0.07 -0.03  0.32  0.17  0.26
```

```
% SE      0.89  1.00  0.74  1.74  3.71  4.63  6.16  4.52  4.90  5.16  2.74  1.23
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.65  2.20  2.37  2.09  2.20  2.02  2.39  1.92  2.36  2.36  2.48  1.88
SKEW      1.24 -0.01  1.41  0.19  0.25  0.34  0.34 -0.04  0.21  0.40  0.29  0.70
% SSE     0.37  0.41  0.10  0.26  0.65  1.07  1.60  1.38  1.36  1.21  0.92  0.68
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.48  1.23  1.77  2.26  1.71  1.62  2.12  1.90  1.95  2.07  2.66  2.17
SKEW      0.36 -0.33  1.16  1.32 -0.03  0.39  0.53 -0.43  0.41  0.91  0.27  0.27
% S       0.23  0.24  0.14  0.24  0.41  0.54  0.55  0.38  0.48  0.65  0.71  0.60
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.31  0.56  1.11  0.91  1.24  1.01  2.04  1.65  1.67  1.15  1.37  2.03
SKEW      0.01 -0.44 -0.20  0.13  0.22  0.42  1.30  2.02  1.51  0.58  1.99  0.55
% SSW     0.44  0.13  0.19  0.21  0.39  0.18  0.33  0.04  0.12  0.13  0.29  0.19
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.46  0.56  2.90  0.88  1.43  0.68  0.90  0.00  0.00  0.95  2.19  0.90
SKEW      0.51  0.00  0.63 -0.92  0.14 -0.38  0.61  0.00  0.00  1.32  0.90  0.00
% SW      0.86  0.41  0.13  0.11  0.32  0.17  0.14  0.02  0.10  0.18  0.64  0.29
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.69  1.79  0.00  1.02  1.27  0.71  0.00  0.00  0.00  1.14  2.37  1.23
SKEW     -0.43 -0.03  0.00 -0.27 -0.03  0.78 -3.00  0.00  0.00  2.66  0.40  0.00
% WSW     0.70  0.14  0.32  0.05  0.52  0.15  0.08  0.00  0.00  0.31  1.03  0.35
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.82  0.56  2.49  0.00  1.13  0.00  0.42  0.00  0.00  1.47  2.58  2.91
SKEW      0.01 -0.20  0.00  0.00 -0.49 -3.00 -1.83  0.00  0.00  0.03 -0.18 -0.66
% W       1.79  0.96  0.52  0.25  0.54  0.49  0.21  0.01  0.00  0.28  2.27  1.35
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   3.41  2.55  1.36  1.64  1.60  1.13  0.56  0.00  0.00  1.57  3.17  2.74
SKEW      0.33  0.46 -0.80 -0.57  0.16 -0.67  0.00  0.00  0.00  0.47 -0.14  0.13
% WNW     1.38  1.00  0.45  0.17  0.30  0.24  0.07  0.02  0.10  0.18  1.26  1.52
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.56  2.21  1.51  1.58  0.73  1.36  0.00  0.00  0.00  1.53  3.26  2.94
SKEW      0.50  0.14  0.38 -0.34 -0.51  0.73  0.00  0.00  0.00 -0.38  0.32 -0.13
% NW      2.70  1.49  0.39  0.35  0.79  1.08  0.04  0.04  0.10  0.30  1.40  3.46
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.27  2.53  1.73  1.22  1.23  1.65  1.24  0.00  0.00  1.31  3.00  2.43
SKEW     -0.28 -0.16  0.13  0.33  0.38  0.29  0.08  0.00  0.00  1.66  0.57  0.02
% NNW     2.52  0.78  0.60  0.85  0.92  0.88  0.13  0.30  0.15  0.96  1.38  2.42
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.21  2.68  1.61  1.39  1.54  1.87  0.85  0.99  0.74  1.82  2.32  1.96
SKEW      0.25  1.06  0.27  0.51  0.21 -0.27  1.15 -0.25 -2.42  0.29  0.19  0.66
CALM      0.61  0.07  0.19  0.70  0.67  0.39  0.64  0.12  0.41  0.85  1.18  1.42
CANTON ISLAND PI    1.000  MAJURO ATOLL  PI    0.000  CANTON ISLAND PI    0.000
```

B.2 Updated Input for Ditchling Road

```
 DITCHLING ROAD UK (updated)             915001 0
 LATT=  51.00 LONG=   0.13 YEARS= 09. TYPE= 1
 ELEVATION =  105. TP5 = 4.29 TP6= 6.00
 MEAN~P   0.11  0.11  0.18  0.21  0.17  0.15  0.16  0.13  0.24  0.29  0.19  0.29
 S DEV P  0.21  0.17  0.18  0.19  0.17  0.23  0.28  0.28  0.27  0.34  0.27  0.23
 SQEW  P  1.92  1.54  1.54  2.94  2.17  2.62  3.94  2.23  2.09  2.50  1.73  1.91
 P(W/W)   0.66  0.71  0.65  0.62  0.60  0.57  0.53  0.53  0.63  0.63  0.66  0.63
 P(W/D)   0.32  0.20  0.36  0.21  0.27  0.22  0.23  0.23  0.28  0.30  0.33  0.34
 TMAX AV 43.29 43.00 46.99 52.59 58.32 63.82 67.44 67.19 63.01 57.02 50.07 46.38
 TMIN AV 34.38 33.96 36.86 39.96 45.45 51.17 54.84 54.97 51.69 46.81 40.77 38.14
 SD TMAX  5.76  5.52  4.18  6.11  6.32  6.65  6.08  5.14  4.17  4.48  5.24  4.71
 SD TMIN  6.63  6.02  4.95  6.06  4.70  4.50  4.00  3.98  4.65  5.39  6.64 17.96
 SOL.RAD   81.  137.  234.  399.  483.  530.  518.  465.  312.  187.  101.   66.
 SD SOL   16.4  17.0  22.1  31.8  38.8  37.6  39.4  31.8  21.5  11.8  15.8  17.6
 MX .5 P  0.27  0.18  0.23  0.23  0.27  0.33  0.42  0.58  0.43  0.45  0.34  0.30
 DEW PT  35.21 34.76 36.71 38.45 43.04 47.32 50.04 50.06 49.20 44.50 39.94 37.49
Time Pk  0.185 0.261 0.351 0.439 0.509 0.588 0.649 0.725 0.800 0.869 0.926 1.000
% N       5.02  2.85  1.71  3.82  2.17  1.40  0.62  0.41  1.26  2.23  3.26  5.04
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
```

```
STD DEV   2.16  1.86  1.79  1.67  1.65  1.68  1.20  1.60  1.47  1.88  1.95  1.89
SKEW      0.22  0.28  0.16  0.18  0.01  0.30 -0.08 -0.01  0.65  0.23  0.41  0.31
% NNE     5.92  8.19  6.04  8.17  6.13  4.75  1.83  2.06  3.28  5.42  5.20  7.69
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.04  2.10  1.83  1.77  2.03  1.74  1.75  2.00  1.91  1.83  2.10  1.97
SKEW     -0.01 -0.01 -0.06  0.05  0.09 -0.07  0.32 -0.02  0.02  0.10  0.15  0.11
% NE     16.39 17.41 20.24 17.13 16.02 10.45  7.49  7.34  9.60 11.66 14.72 16.32
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.97  2.14  1.82  1.71  1.96  1.92  1.93  1.91  1.86  1.85  2.15  1.92
SKEW     -0.14  0.13 -0.05  0.22  0.21  0.14  0.28 -0.05 -0.03  0.22  0.23 -0.05
% ENE    27.65 30.14 34.63 27.20 26.30 21.39 20.20 18.94 21.34 22.85 25.11 25.31
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.85  1.88  1.77  1.76  1.70  1.77  1.82  1.67  1.71  1.72  1.83  1.91
SKEW      0.06 -0.01  0.12  0.12  0.10 -0.13  0.15  0.08  0.09  0.17  0.22 -0.13
% E      24.64 28.68 29.12 28.99 26.83 33.93 36.80 37.28 35.21 30.74 25.13 24.26
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.95  2.00  1.84  1.84  1.78  1.84  1.87  1.84  1.97  1.94  1.97  2.04
SKEW      0.05  0.00  0.31  0.13  0.05 -0.02  0.04 -0.12  0.03  0.11  0.18 -0.04
% ESE     7.82  6.08  4.62  9.71 13.47 18.20 23.12 27.05 21.47 16.84 12.72  7.87
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.96  1.60  1.88  1.86  2.04  1.88  1.83  1.88  1.85  1.88  1.96  1.97
SKEW      0.02  0.07  0.51  0.11  0.16  0.07  0.10 -0.07 -0.03  0.32  0.17  0.26
% SE      0.89  1.00  0.74  1.74  3.71  4.63  6.16  4.52  4.90  5.16  2.74  1.23
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.65  2.20  2.37  2.09  2.20  2.02  2.39  1.92  2.36  2.36  2.48  1.88
SKEW      1.24 -0.01  1.41  0.19  0.25  0.34  0.34 -0.04  0.21  0.40  0.29  0.70
% SSE     0.37  0.41  0.10  0.26  0.65  1.07  1.60  1.38  1.36  1.21  0.92  0.68
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.48  1.23  1.77  2.26  1.71  1.62  2.12  1.90  1.95  2.07  2.66  2.17
SKEW      0.36 -0.33  1.16  1.32 -0.03  0.39  0.53 -0.43  0.41  0.91  0.27  0.27
% S       0.23  0.24  0.14  0.24  0.41  0.54  0.55  0.38  0.48  0.65  0.71  0.60
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.31  0.56  1.11  0.91  1.24  1.01  2.04  1.65  1.67  1.15  1.37  2.03
SKEW      0.01 -0.44 -0.20  0.13  0.22  0.42  1.30  2.02  1.51  0.58  1.99  0.55
% SSW     0.44  0.13  0.19  0.21  0.39  0.18  0.33  0.04  0.12  0.13  0.29  0.19
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.46  0.56  2.90  0.88  1.43  0.68  0.90  0.00  0.00  0.95  2.19  0.90
SKEW      0.51  0.00  0.63 -0.92  0.14 -0.38  0.61  0.00  0.00  1.32  0.90  0.00
% SW      0.86  0.41  0.13  0.11  0.32  0.17  0.14  0.02  0.10  0.18  0.64  0.29
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.69  1.79  0.00  1.02  1.27  0.71  0.00  0.00  0.00  1.14  2.37  1.23
SKEW     -0.43 -0.03  0.00 -0.27 -0.03  0.78 -3.00  0.00  0.00  2.66  0.40  0.00
% WSW     0.70  0.14  0.32  0.05  0.52  0.15  0.08  0.00  0.00  0.31  1.03  0.35
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   1.82  0.56  2.49  0.00  1.13  0.00  0.42  0.00  0.00  1.47  2.58  2.91
SKEW      0.01 -0.20  0.00  0.00 -0.49 -3.00 -1.83  0.00  0.00  0.03 -0.18 -0.66
% W       1.79  0.96  0.52  0.25  0.54  0.49  0.21  0.01  0.00  0.28  2.27  1.35
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   3.41  2.55  1.36  1.64  1.60  1.13  0.56  0.00  0.00  1.57  3.17  2.74
SKEW      0.33  0.46 -0.80 -0.57  0.16 -0.67  0.00  0.00  0.00  0.47 -0.14  0.13
% WNW     1.38  1.00  0.45  0.17  0.30  0.24  0.07  0.02  0.10  0.18  1.26  1.52
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.56  2.21  1.51  1.58  0.73  1.36  0.00  0.00  0.00  1.53  3.26  2.94
SKEW      0.50  0.14  0.38 -0.34 -0.51  0.73  0.00  0.00  0.00 -0.38  0.32 -0.13
% NW      2.70  1.49  0.39  0.35  0.79  1.08  0.04  0.04  0.10  0.30  1.40  3.46
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.27  2.53  1.73  1.22  1.23  1.65  1.24  0.00  0.00  1.31  3.00  2.43
SKEW     -0.28 -0.16  0.13  0.33  0.38  0.29  0.08  0.00  0.00  1.66  0.57  0.02
% NNW     2.52  0.78  0.60  0.85  0.92  0.88  0.13  0.30  0.15  0.96  1.38  2.42
MEAN      2.79  2.87  2.87  2.62  2.67  2.29  2.29  2.20  2.32  2.37  2.73  2.80
STD DEV   2.21  2.68  1.61  1.39  1.54  1.87  0.85  0.99  0.74  1.82  2.32  1.96
SKEW      0.25  1.06  0.27  0.51  0.21 -0.27  1.15 -0.25 -2.42  0.29  0.19  0.66
CALM      0.61  0.07  0.19  0.70  0.67  0.39  0.64  0.12  0.41  0.85  1.18  1.42
CANTON ISLAND PI    1.000  MAJURO ATOLL  PI    0.000  CANTON ISLAND PI    0.000
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Appendix C

EUROSEM Input Data

C.1 SYSTEMS

NELE [1] This defines the total number of elements in the catchment. Its value should be the same as the number of elements entered under ELEMENT NUM. (J) in the Rainfall Data File (XXX.pcp). Since, in this example, only one slope plane (Woodingdean D) was being considered, we entered NELE = 1.

Woodingdean site is divided into 9 slopes (D L).

NPART [0] This relates to a component of the KINEROS model which describes the settling of sediment in ponds. It is not used in the present version of EUROSEM. A value of 0 should always be set here.

CLEN (m) [135] This is the characteristic length of overland flow and represents the longest possible length in a series of cascading planes or channels. Since the example erosion plot was being treated as one slope element, CLEN was set here as equal to the downslope length of the plot (the maximum lengths of longest channel), i.e. 135 m.

TFIN (min) [870] This is the total computational time (min) for which the model is to be run. Its value must be less than the end-time of the last time-depth pair in the Rainfall Data File. The value of TFIN will depend upon the duration of the storm and the response time of the catchment. It should be sufficient to contain the hydrograph of surface runoff and should therefore extend from the start of the rainfall to the time that surface runoff on the hillslopes ceases. For the storm considered here, the last time-depth pair ends at 900 minutes, so we set TFIN = 870 min. Actual rainfall duration for the storm is 870 minutes. 30 minutes were added to indicate the end of storm (no rain for 30 min).

DELT (min) [1] This defines the time increment used in the simulations. Ideally, this should be as short as possible. However, the total number of time steps, defined as TFIN/DELT should not exceed 1000 in which case the model will pause and a warning message will appear. For this example, I choose a value of DELT = 1.0. (870/1 = 870 < 1000)

THETA [0.7] This is a weighting factor used in the finite difference equations in KINEROS for routing overland flow and channel flow. It should have a value between 0.5 and 1.0. A value of 0.7 is recommended and this was the value we chose.

TEMP [2.55] The air temperature (° Celsius) at the start of the storm should be set here. It is used in the model to compute the kinematic viscosity of water. Mean temperature on the day of storm was chosen. (Max = 4.8 ° C and Min = 0.3 ° C)

C.2 OPTIONS

No changes should be made to the entries under this heading. EUROSEM is designed to operate with values of 2 under both entries.

NTIME [2] This is the code for the time units used in the model. NTIME = 1 for seconds and NTIME = 2 for minutes. The value of 2 should always be used with the present version of EUROSEM.

NEROS [2] This allows the user to call or reject the erosion option in the model. With values set at 0 or 1, the erosion option is not called and only the hydrological calculations are made. A value of 2 calls the erosion option which, in this case is EUROSEM.

C.3 COMPUTATION ORDER

This heading describes the order in which the plane and channel elements comprising the catchment must be organised to provide the correct cascading sequence for the movement of runoff and sediment downslope and downstream.

COMP. ORDER (NLOG) [1] This denotes the order of calculation. Each entry must therefore be in numerical sequence.

ELEMENT NUM. (J) [1] This defines the corresponding element number for each entry in the sequence. The element numbers need not be in numerical order. The total number of elements listed here should be the same as the total number entered under ELE. NUM. (J) in the Rainfall Data File and correspond to the number entered under NELE above. Since only one slope plane was being considered at Woburn, NLOG was set to 1 and ELEMENT NUM. was therefore also equal to 1.

C.4 ELEMENT WISE INFO

This heading gives the data on the catchment characteristics of each element. The number by which each element is known must be the same as that listed above under ELEMENT NUM, where the computational order is defined, and also under ELE. NUM. (J) in the Rainfall Data File.

J [1] This represents the number of the element. J = 1 for the first element, J = 2 for the second element, and so on. In the example being used here, there was only one element, so J = 1.

NU [0] This denotes the number of the element which contributes runoff and sediment to the upslope boundary. Since there was only one element, there were no upslope contributing elements, so NU = 0.

NR [0] This entry applies to elements which are channels and denotes the number of the hillslope elements contributing flow to the channel from the right-hand side when viewed in the direction of flow, i.e. facing downstream. For hillslope elements, as here, NR = 0.

NL [0] This entry similarly applies to channels and denotes the number of the hillslope element contributing flow to the channel from the left-hand side. For hillslope elements, as here, NL = 0.

NC1 [0] This entry also applies to channels and denotes the number of the first channel element contributing flow to the channel from upstream. For hillslope elements, NC1 = 0.

NC2 [0] This entry denotes the number of the second channel element contributing flow to the channel from upstream. It is relevant for channels downstream of a confluence so that there are two contributing channel elements at the upstream end. For hillslope elements, NC2 = 0.

NPRINT [1] This controls the amount of information provided in the auxilary output file. In our case it is set to 1.

XL (m) [135.0] This is the length of the element (in meter). Since the erosion plot was 135 m long, XL = 135.0.

W (m) [50] This is the width of the element (m). Since the erosion plot was 50 m wide, W = 50.0. It should be noted that W = 0.0 if the element being described is a channel.

S [0.14] This is the average slope of any rills on the element (m/m), measured in the direction of maximum slope, i.e. at right angles to the contour. Since the average slope of the plot was measured in the field at 14 per cent, we entered S = 0.14.

ZR [0] This is the side slope of the right-hand side of the channel, assuming a trapezoidal shape and expressing the slope as 1:ZR. Since we were dealing with a plane element, there were no channels, so ZR = 0.

ZL [0] This is the side slope of the left-hand side of the channel, assuming a trapezoidal shape and expressing the slope as 1:ZL. Since we were dealing with a plane element, there were no channels, so ZL = 0.

BW [0] This is the bottom width (m) of the channel, assuming a trapezoidal shape. Since we were dealing with a plane element, there were no channels, so BW = 0.0.

MANN (Rill) [0.125] This is the value of Manning's n for the rill channels (concentrated flow paths) on the element, taking account of the combined effects of soil particle roughness, surface microtopography and plant cover on the element. For the sandy loam soil in a smooth seed-bed, a typical value would be n = 0.015. For wheat, n ranges from 0.01 to 0.30, depending on the percentage cover and planting density. For the smooth seedbed and 10 per cent cover prevailing at the time of the storm, we estimated a value at the lower end of the range, e.g. 0.04. The value for Manning's n should be further adjusted to take account of rock fragments or stones in the surface soil, using equation A3.2 in appendix 3.

Mann (IR) [0.170] This is the value of Manning's n for the interrill area of the element, again taking into account soil particle roughness, surface microtopography and plant cover. For the smooth surface and cover of the element in question, the same value was chosen as for Manning's n in the rills. We therefore entered IRMANN = 0.04. As with the case above, the Manning's n value should be adjusted, if necessary, for rock fragments or stones in the surface soil, using equation A3.2 in appendix 3. No such adjustment was needed for Woburn. You should note that the model will further adjust the value of IRMANN to take account of the level of roughness on the interrill area, as expressed by the downslope roughness ratio, RFR (Appendix 6).

FMIN (mm/h) [3.0] This is the saturated hydraulic conductivity of the soil (mm/h). This should be the value for the soil itself and should not be adjusted for plant cover or stoniness. These adjustments are made within the model itself, as functions of input data on PBASE and ROC respectively. If FMIN has been measured for soils with a vegetation or stone cover, the measured value should be used. The input values for PBASE and ROC should then be set to zero so that no further adjustment is made to the FMIN value within the model. Effective hydraulic conductivity of the soil should be 3 mm/h (from WEPP output).

G (mm) [480.0] This is the effective net capillary drive of the soil (mm), as described in Section 3.3.1. From Table A4.1, a value of 480 was chosen for a silt loam soil, so here G = 480.

POR [0.5] This is the porosity of the soil (% v/v). From Table A4.1, a value of 0.50 was chosen for a silt loam soil and we entered POR = 0.50.

ThI [0.4] This is the volumetric moisture content of the soil at the start of the storm. This has to be estimated in relation to the time since it last rained and the speed with which the soil dries out. As explained in Appendix 4, THI will take a value between the maximum moisture content of the soil (THMX) and the moisture content at wilting point. Since the storm occurred in the middle of a wet spell of weather, the soil had had little opportunity to dry out between storms. A rather high value of THI = 0.4 was therefore chosen.

ThMX [0.42] This is the maximum moisture content of the soil. From Table A4.1, we chose a value of THMX = 0.42.

ROC [0.0] This is the proportion (% v/v) of the soil occupied by stones and rocks. Since the silt loam soil at Woodingdean is very stony, we could have entered ROC = 0.381 (from the WEPP input, andover.sol). However, a value of ROC = 0.0 was used as the input value for FMIN is assumed as a measured one, which already takes account of the presence of rock fragments or stones.

RECS (mm) [1.0] This is the infiltration recession factor and is defined as the average maximum local difference in microrelief (mm). Based on field measurements of surface roughness (Appendix 6), a value of RECS = 20.0 was selected. It should be noted that a value of RECS > 0 must always be entered.

DINT (mm) [3.0] This is the maximum interception storage of the plant cover (mm). From Table A7.1, for winter-sown wheat, a value of DINTR = 3.0 was chosen.

DEPNO [15.0] This denotes the average number of rills (concentrated flow paths) across the width of the slope plane. Since the erosion plot is ploughed up and down slope, the plough furrows act as concentrated flow paths. Based on field observations, an average of ten paths was recorded, using the procedure shown in Appendix 8. A value of DEPNO = 15.0 was therefore entered.

RILLW (m) [0.02] This is the average bottom width (m) of a concentrated flow path or rill. A arbitrary value of RILLW = 0.02 was entered. A flat surface would be assigned a value of RILLW = 0.0.

RILLD (m) [0.03] This is the average depth (m) of a concentrated flow path or rill. A arbitrary value of RILLD = 0.03 was entered.

ZLR [10.0] This denotes the average side slope of a concentrated flow path (rill), expressed as 1:ZLR. A arbitrary value of ZLR = 10.0 was entered.

RS [1.0] If RS = 0, the model assumes that the values of RILLW and RILLD entered above apply for the whole length of the element. If RS = 1, the model assumes the values apply to the rill at the lower end of the element and scales the values to smaller dimensions with distance upslope. In this case, the scaling option was selected, so we entered RS = 1.

RFR [1.0] This is the downslope roughness ratio. Based on field measurements, using the procedure described in Appendix 6 and illustrated in Figure A6.1, a value of RFR = 1.0 was obtained and entered. Although this value is much lower than those listed in Table A6.1, it is a typical value for a relatively smooth surface. As stated earlier when choosing a value for Manning's n, the condition of the ground at the time of the storm was a smooth seed-bed flattened by several months of raindrop impact.

SIR (m/m) [0.2] This is the interrill slope. For unrilled plane elements, this is the average slope of the plane. For channel elements, this is the average slope of channel. For a plane element with rills, SIR is defined as the average ground slope followed by overland flow as it passes over the interrill area into the rills (see Appendix 2). The average slope of the rills should be entered under S. A arbitrary value of SIR = 0.5 was entered.

COVER [0.3] This is the effective percentage canopy cover of the vegetation. Strictly it refers to the proportion (between 0 and 1) of the ground surface obscured by the vegetation when viewed vertically from above. The value should take account of ground vegetation, mulches and any litter layer as well as trees and bushes. Since, at the time of the storm, this was estimated at 30 per cent, a value of COVER = 0.3 was entered.

SHAPE [1] This refers to the shape of the leaves. SHAPE = 1 for bladed leaves and needle leaves. SHAPE = 2 for broad leaves. Since the crop was wheat, we entered SHAPE = 1. Conceptually, the SHAPE factor describes, in a simplified way, the relationship between the size of the leaves and the median volume drop diameter of the rainfall. A value of 0, to be entered when there is no vegetation cover, will cause stemflow to be set zero.

PLANGLE (degree) [85.0] This is the average acute angle (degrees) between the plant stems and the ground surface. Based on the model manual (Table A7.2), a mean value of PLANGLE = 85° was entered (wheat = 80–90).

PLANTBASE [0.0] This is the percentage basal area of the vegetation cover. From Table A7.3, we can see that the value for small grains (wheat, barley, rice) ranges from 0.2 to 0.3, depending on the planting density. As this may be assumed to be high, a value of 0.3 is chosen. Since the percentage plant cover was only 30 per cent, the value was reduced accordingly and we could have entered PLANTBASE = 0.09. However, it should be noted that if the value entered for FMIN has been determined in the field for vegetated conditions, PLANTBASE should be set to 0.0. This avoids further adjustment of the FMIN value within the model to allow for the effect of the vegetation cover.

PLANTH (cm) [100] This is the average height of the plant canopy (cm) above the ground surface. From Table A7.2, wheat has a height of 50 – 150 cm. Since, the purpose is to describe the fall height of intercepted raindrops, any ground vegetation, mulches and litter layer should be considered. A value of 100 (cm) was entered for this example.

DERO (m) [2.0] This is the maximum depth (m) to which erosion can proceed before a resistant or non-erodible layer (e.g. plough pan or concretionary horizon) below the soil surface. Once erosion reaches this depth, the model prevents further downcutting by rills; from then on the rills are only able to erode by widening their channels. Since there are layers with high clay contents from 2 m, we entered DERO = 2.0.

ISTONE [+] An indicator of the effect of rock fragments on the surface of the soil on the saturated hydraulic conductivity (see Appendix 5). A value of +1 should be used where the rock fragments sit on the surface and protect the soil from structural breakdown due to raindrop impact; or where the rocks either sit on or are fully embedded in a soil with high macroporosity, e.g. due to recent tillage. In this instance, the rock fragments will enhance infiltration. A value of -1 should be used where the rocks are partially embedded within or sit on top of a sealed surface which will reduce infiltration. When PAVE value is set to zero, this value is not considered in the model.

D50 (μm) [35.0] This is the median particle size of the soil as obtained from standard particle-size analysis, using the USDA system to define textural classes (i.e. clay: < 0.002 mm; silt: 0.002 - 0.05 mm; sand 0.05 - 2.00 mm). A value of D50 = 35 was entered.

EROD (g/J) [0.8] This is the detachability of the soil particles by raindrop impact (g/J). From Table A9.1, for a silt loam soil, a minimum value of EROD = 0.8 was selected.

SPLTEX [2.0] This is the value of the exponent relating detachment of soil particles by raindrop impact to the depth of water on the soil surface. The current version of EUROSEM uses a constant value of 2.0 for this exponent.

COH (kPa) [6.3] This is the cohesion of the soil as measured in the field with a torvane (Soil Test CL-600) after the soil has been saturated (see Appendix 9). Guide values for soils with different textures are given in Appendix 9. The value should be adjusted to take account of the effects of the root system of the vegetation. From field measurements on the bare saturated silt loam soil (compacted), cohesion is low at about 6.0 kPa. From Table A9.3, assuming that wheat has a similar effect to barley, an increase in cohesion of between 0.2 and 0.6 kPa may be expected as a result of root reinforcement. For a crop at the stage of 30 % cover, we might estimate an increase at the lower end of the range, say 0.3 kPa. If this is added to the cohesion value for the bare soil, we get a total cohesion of 6.0 + 0.3 kPa = 6.3 kPa. A value of COH = 6.3 was therefore entered.

RHOS (Mg/m3) [2.65] This is the specific gravity of the sediment particles. This is normally set at 2.65 Mg/m3.

PAVE [0.0] This is the fraction of the surface occupied by non-erodible material (e.g. rock fragments, concrete, tarmac). It is used in EUROSEM to reduce the rate of soil detachment by raindrop impact in direct proportion to the area occupied by non-erodible surfaces and also to influence the way rock fragments affect the saturated hydraulic conductivity of the soil (see ISTONE). This value was set to zero to prevent any further adjustment of FMIN.

SIGMAS [0] This is the standard deviation of the sediment particle diameter (μm) for any element immediately upslope of a pond. It is used within KINEROS for modelling the process of sedimentation in a pond or reservoir. Since current version of EUROSEM does not deal with ponds, SIGMAS was set = 0.0.

MCODE [0] The value chosen for MCODE allows the user to choose the equations used in EUROSEM to simulate sediment transport by interrill flow. MCODE = 1 selects the equations proposed by Everaert (1992) which relate specifically to interrill flow. MCODE = 0 selects the equations proposed by Govers (1990) for rill flow and applies them to both interrill and rill flow. See the model documentations for more details.

Appendix D

RillGrow Input Data