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. Within-Storm Intensity Patterns (WSIPs) affect soil erosion amount, although runoff was not much affected. An additional daily rainfall event with Within-Storm Gaps (WSGs) is also selected to investigate effects of WSG removals on soil erosion. For a given amount of rainfall, events with constant low intensity (constant WSIP) produced dramatically less erosion: thus it appears that assuming a constant (or averaged) intensity throughout a storm does not provide a good representation of a real rainfall with its continuously varying intensity. Analyses of outputs from WEPP simulations revealed a problem that WEPP modifies original rainfall intensity and, thus, simulates erroneous runoff and erosion rates. Future soil erosion rates are estimated using WEPP and CLIGEN data. 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 also known as MX.5P. 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. This research assists in improving the performance of erosion models with respect to changes of rainfall intensity by highlighting where current problem exists. In conclusion, greater knowledge found here will, once future changes in rainfall intensity become better known and appropriate rainfall data become available, improve our ability to estimate future rates of erosion.

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PART I

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 (Pruski and Nearing, 2002*a*), 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; Favis-Mortlock and Guerra, 1999; Pruski and Nearing, 2002*a*,*b*; O'Neal *et al.*, 2005). This is unlikely to be the case. Intensities may change and/or the frequency of occurrence of high-intensity events may change (Karl *et al.*, 1995; Houghton *et al.*, 1996; Watson *et al.*, 1998; Karl and Knight, 1998; Osborn and Hulme, 1998, 2002). 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). 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).

Few studies have attempted to quantify changes in future rainfall intensity (Karl *et al.*, 1995; Houghton *et al.*, 1996; Watson *et al.*, 1998; Karl and Knight, 1998; Osborn and Hulme, 1998, 2002). Results from these studies suggest that, in some regions at least, more (or similar) rainfall than at present will occur on fewer raindays—implying an increase in the frequency of heavy rainfall. 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.

This thesis, therefore, aims to address some of the issues involved in predicting future soil erosion as a response to future changes of rainfall intensity. More detailed aims and issues associated with achieving those aims are presented at the end of Chapter 2. Prior to Chapter 2, topics that are related to soil erosion processes, rainfall intensity, climate changes and erosion prediction models are discussed in the following sections.

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. However, 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. As the flow travels down a hillslope, it is able to carry soil materials away mainly by shear stress although other sub-processes also contribute (Kinnell, 2000, 2005*a*, see also Figure 1.1). 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 (Boardman, 2001, 2003).

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 more distinctive 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.

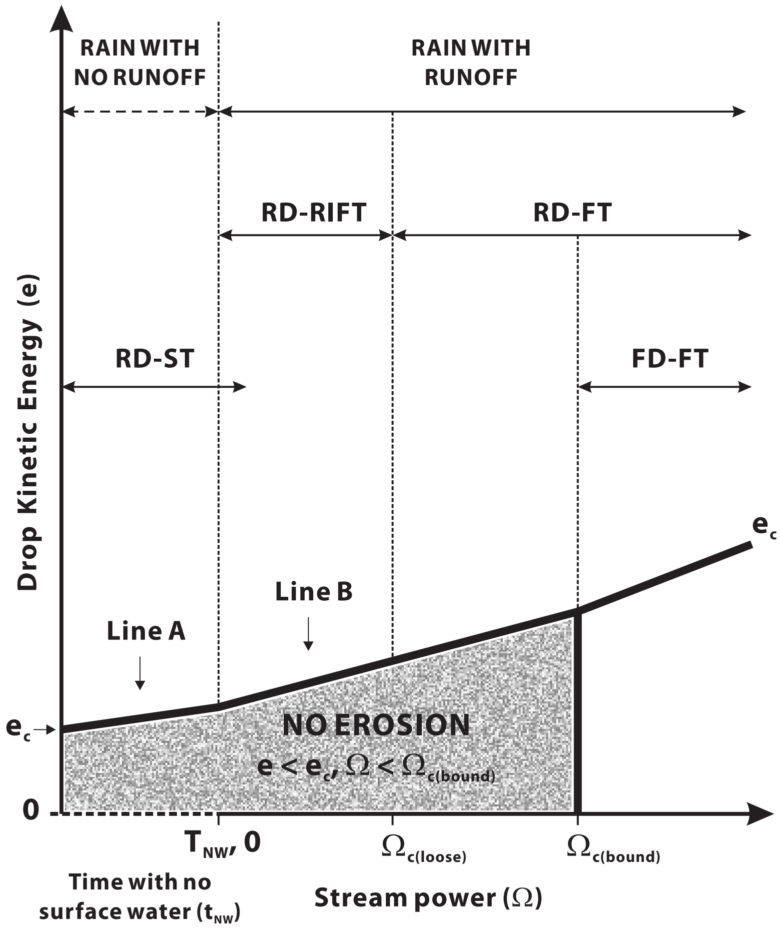


Figure 1.1 Detachment and transport processes associated with variations in raindrop and flow energies. T_{NW}: total time when rain falls and there is no surface water. e_c: critical raindrop energy to cause detachment; raindrop-induced erosion occurs when drop energy is equal or greater than e_c. Line 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*).

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 dominate. 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 loses 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 ($\Omega_{c(\mathrm{bound})}$) 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 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 by splash 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, modelling studies, as rainfall intensity is the only easily modifiable control on rainfall energy in such studies (Laflen *et al.*, 1997; Morgan *et al.*, 1998*b*).

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

This section provides examples of some notable erosion events which are documented in selected publications.

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.

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.

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.

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.

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.

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; Jones and Reid, 2001; IPCC, 2001*b*,*a*, 2007*a*,*b*). This increase in global average precipitation has been based on the assumption that an increasing global-mean temperature will intensify the hydrological cycle (Nearing *et al.*, 2005). 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, 2001*b*, 2007*b*). Climate models are also predicting a continued increase in intense precipitation events during the 21st century (IPCC, 2001*a*, 2007*a*).

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 (2001*a*,*b*) 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 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 (e.g., heavy showers, gusts and tornadoes) are rare and occur on the synoptic and even smaller temporal and spatial resolutions (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 resolution 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 (2001*a*) 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 Background and Categories of Erosion Models

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 resolutions (i.e. plot, field and catchment-scale) has been neglected because it is a difficult task (Boardman, 1996).

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 (also can be termed as 'unknown unknowns') 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 (also can be termed as 'known unknowns') 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 (or known unknowns) by studying and obtain absolute knowledge, we will still not be able to predict future weather

Table 1.1 Types of erosion 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.

perfectly because of the aleatory uncertainty (unknown unknowns).

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

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 the physical system Conceptual issues about the physical system are considered by determining all possible factors that might affect the system.

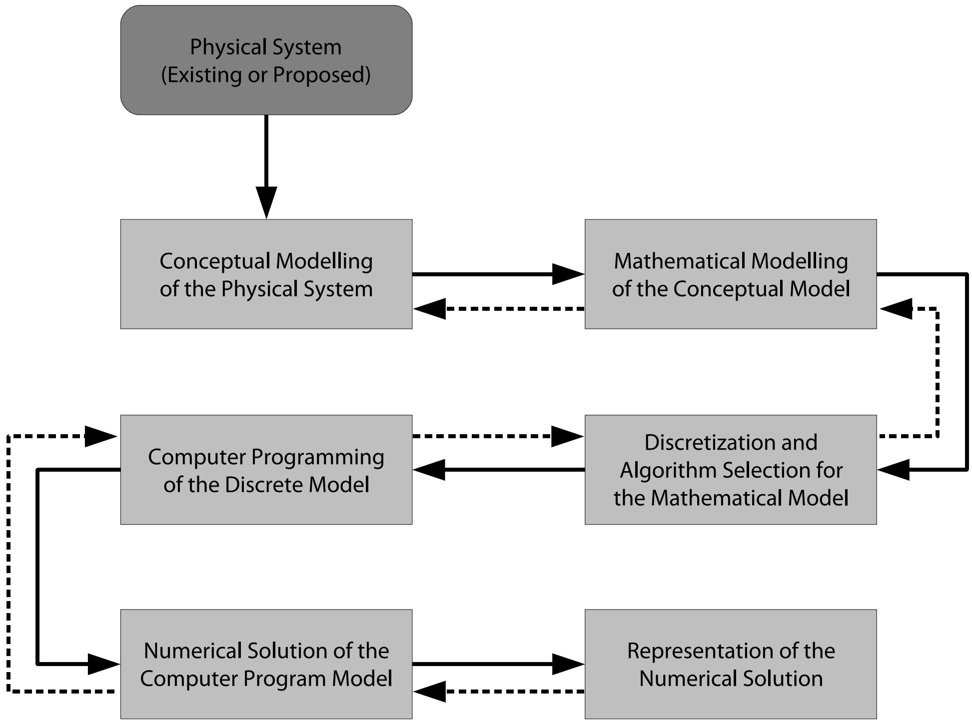


Figure 1.2 Proposed phases for computational modelling and simulation. (From Oberkampf *et al.*, 2002)

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 such as the WEPP (Water Erosion Prediction Project) model, which is also reviewed in this chapter.

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

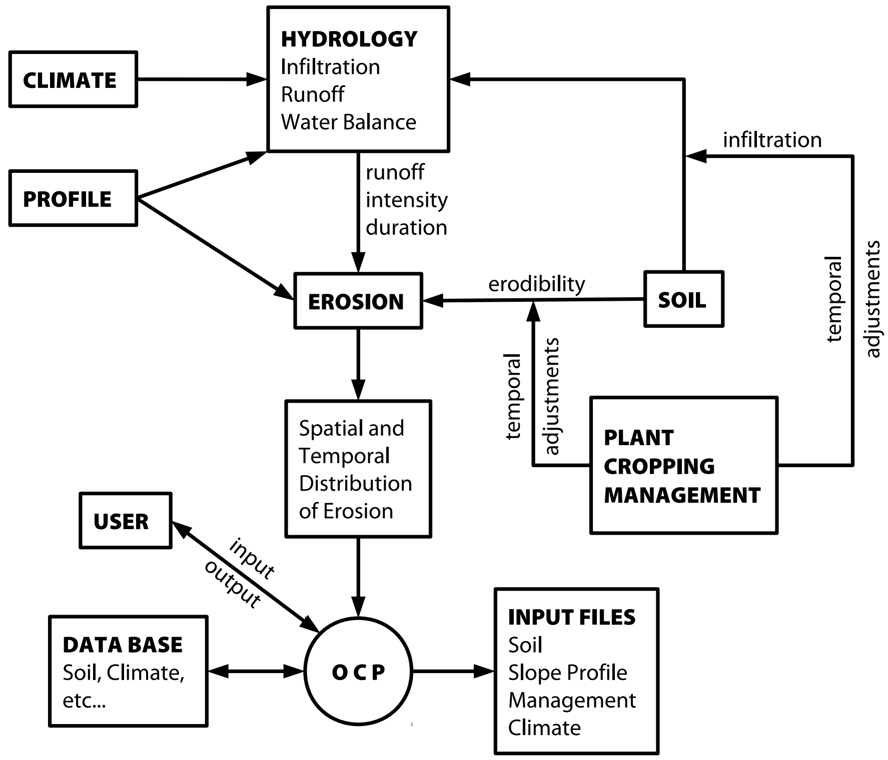


Figure 1.3 Flow chart illustrating the components of the hillslope profile of the WEPP model (from Lane and Nearing, 1989). OCP stands for Operational Computer Program

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:

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

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. The current version of the WEPP model is 2010.1[1].

[1]http://www.ars.usda.gov/Research/docs.htm?docid=10621, Accessed in February 2012

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).

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 (Nicks *et al.*, 1995; Yu, 2000). 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

Table 1.2 Precipitation parameters required by CLIGEN to generate WEPP precipitation inputs (from Nicks *et al.*, 1995)

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

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[2]. This is the version used in this research. However, this version is not the current version any longer. The current version of CLIGEN is 5.3[3].

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 (Morgan *et al.*, 1998*b*). 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*b*). It can be applied to a small field and up to a small catchment.

EUROSEM requires a one-minute resolution breakpoint rainfall data ideally for the rainfall storm (Morgan *et al.*, 1998*b*). 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

[2]http://horizon.nserl.purdue.edu/Cligen/, April 2006
[3]http://www.ars.usda.gov/Research/docs.htm?docid=18094, Accessed in February 2012

- 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 1.4.

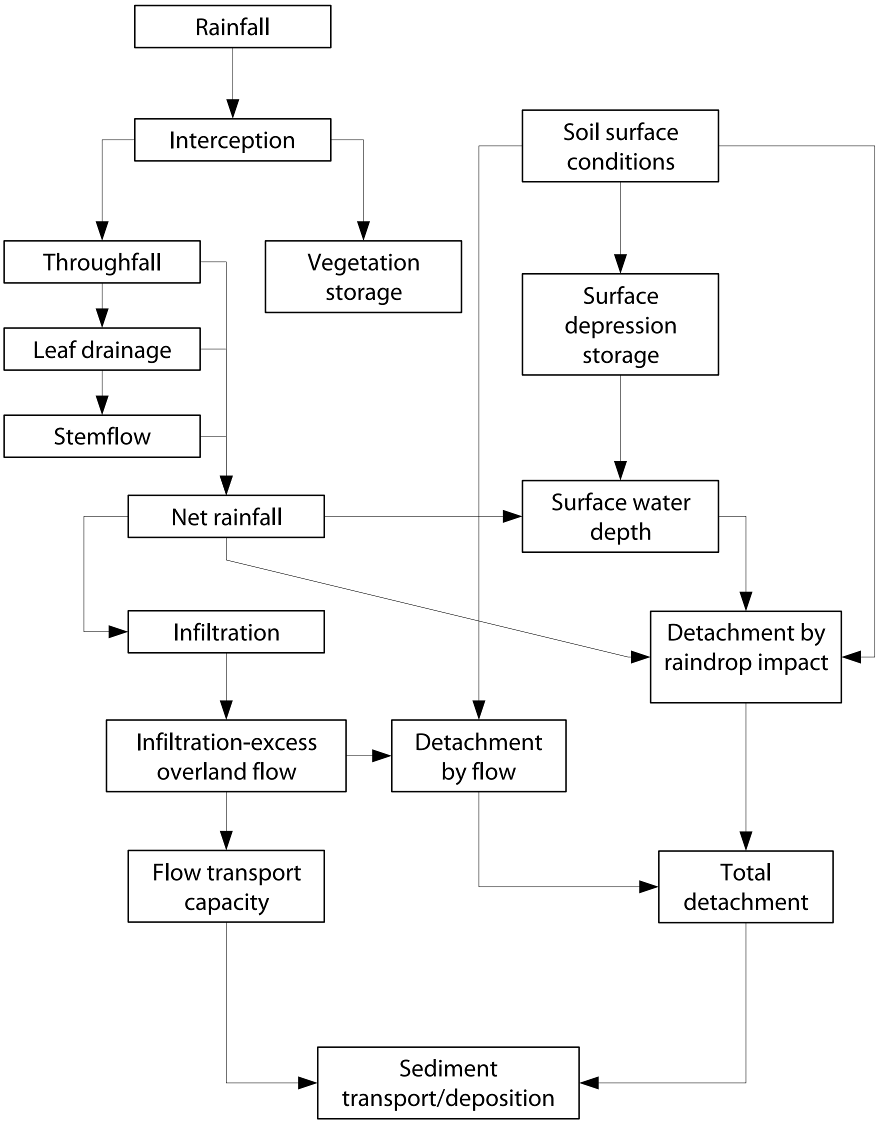


Figure 1.4 Flow chart of EUROSEM (from Morgan *et al.*, 1998*b*)

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 (m³/m³), A is the cross sectional area of the flow (m²), Q is the discharge (m³/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 may be assumed to better represent the spatial and temporal variation 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 (e.g. one-minute breakpoint data) (Morgan *et al.*, 1998*b*), 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 also 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. However, this was not investigated further in this thesis.

Nevertheless, it seems that the unit conversion error is a 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.

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 1.5).

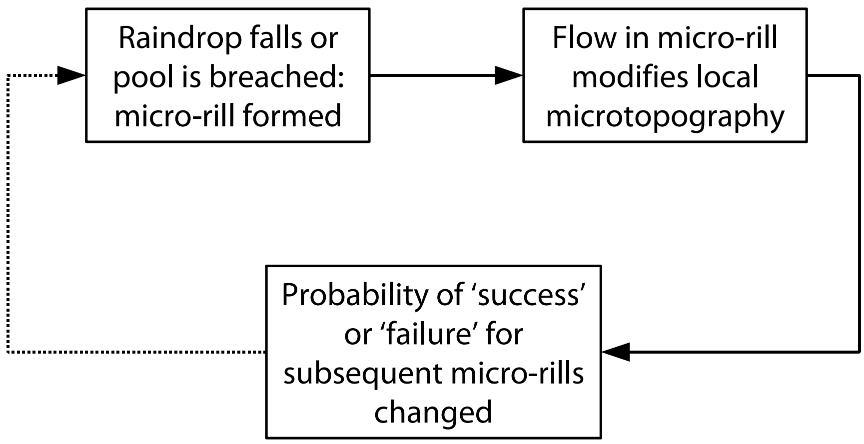


Figure 1.5 The conceptual feedback loop of RillGrow (From Favis-Mortlock, 1998*b*)

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

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.

in effect operates in 'parallel', i.e. concurrently, in a true time domain. RillGrow is now at version 6, parallelised for multiple computer processors (personal communication with David Favis-Mortlock, 2012).

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 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 this aim in this study.

When this research was first begun in 1999, 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 link RCM results and erosion models.

However, after a number of pilot 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. In order to use RCM data for the approach initially proposed, the data should be able to provide rainfall intensity information on a required temporal resolution (i.e. sub-hourly) with an acceptable level of confidence. We determined that RCM data did not hold sufficiently detailed (both temporally and spatially) information for it to be directly used for erosion simulations, and were not reliable enough for this type of approach yet—and still it appears that RCM data are not adequate (Nearing, 2001; Michael *et al.*, 2005; O'Neal *et al.*, 2005).

Thus, another route was taken. As a first approach, in order to obtain rainfall data usable for erosion modelling in terms of resolution and representable as future rainfall, observed rainfall data were analysed to determine trends of rainfall intensity. The idea was that once rainfall intensity trends had been determined, probable scenarios of future rainfall intensity changes could then be built by applying the trend onto observed rainfall intensity.

Rather later, 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 improved erosion models become available, and until more reliable future rainfall data (with high temporal resolution) become available from one source or another.

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 these models are based, using arbitrary changes in rainfall intensity. The idea now is that this will assist in improving the performance of erosion models with respect to changes of rainfall intensity by highlighting where current problem exists.

Consequently, greater knowledge here will, once future changes in rainfall intensity become better known and appropriate rainfall data become available, improve our ability to estimate future rates of erosion.

2.2 Objectives and Rationales

Thus, the main objective of this research is to investigate:

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

To accomplish these aims, the research was carried out in two parts:

- *Rainfall Intensity and Erosion: Model Descriptions and Responses* and
- *Implications for Model-based Studies of Future Climate Change and Soil Erosion*.

In the first part, *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 represent and 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, 2001*b*). 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 this 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 aresult 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, programming 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 research.

The primary purpose of these erosion models (i.e. WEPP, EUROSEM and RillGrow) is of course to simulate the effects of soil erosion by water. Even though each model has its unique way of representing erosion processes, the main design purpose is the same; to simulate real-world erosion processes. However, erosion models are developed for several different purposes; they may be required to:

- Evaluate the role of the different factors which affect erosion, and so improve our understanding of erosion processes
- Be used as predictive tools for unmonitored (or future) landscapes, in order to minimise the agricultural and environmental problems 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 (in theory) with a complete control over those input factors which affect erosion. This is attractive because generally it is not possible to gain complete control over affecting factors in field experiments or in 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 which aim to quantify future erosion (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 random variability ('noise') in the observational data. Therefore, 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 of 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 part of this study, using WEPP, EUROSEM and RillGrow, aims to investigate the:

- information regarding rainfall intensity which is needed to simulate soil erosion,
- responses of selected erosion models to various changes in rainfall intensity,
- representation of the effects of rainfall intensity on erosion within each erosion model,
- applicability of these erosion models for future research.

In the second part, *Implications for Model-based Studies of Future Climate Change and Soil Erosion*, future rainfall intensity scenarios were used to estimate erosion rates using WEPP, one of the soil erosion models used in this research. WEPP is used in the second part 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 second part of this thesis aims to:

- suggest the best currently-available way of investigating impacts of rainfall *intensity* changes on future erosion and
- test this method using scenarios of future change in rainfall intensity.

2.3 Questions To Be Considered

This research addresses 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 a future climate, and that this future climate has different rainfall intensity from the present, what information (both regarding climate, and regarding erosion processes) do we need to make predictions of soil erosion rates under that future climate?

Question 3. From the above, are we in a position to predict soil erosion under the future climate? If not, what more is necessary?

2.4 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 datasets used here for climate analyses, model parametrizations and erosion simulations are obtained from the South Downs, England, 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), that data availability of the site is 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).

3.1.1 Definitions of Intensity and Rainfall Storm

Some preliminary definitions are given before describing rainfall data that are used in this research.

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 rainfall duration (e.g. mm/hr).

Definition of rainfall storm In this research, a rainfall storm is defined as a rainfall event that occurs within 24 hours and lasts no longer than 24 hours. This means that, if a rainfall storm lasts more than a day (i.e. 24 hr), it will be considered as two separate events: one with 24 hr rainfall duration and the other with the duration that remains. This also means that two rainfall events which occur within a predefined 24-hour period will be treated as one rainfall storm. This is because all models used in this research assume that only one rainfall storm occurs per a day. This simplification is unrealistic and may have unknown consequences. However, consequences of this assumption were not covered in this study because they are out of the scope of this research. Nevertheless, this research recognises the existence of this issue and the need for further studies on a more appropriate definition of rainfall storm for soil erosion modelling studies.

Predictions of soil erosion may be improved if we consider rainfall as an event-by-event basis rather than as a daily basis. We need to find a way of separating rainfall events independent of the day rather than taking a whole wet-day (24 hours) as one "event". In this way, soil erosion estimations for the area with dominantly long rainfall duration may be improved.

3.1.2 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): monthly, daily and event data. Details of these data sets are described here because they are used at a certain stage of current research. For example, monthly grid and daily station data are used for the investigation on the trend of rainfall intensity in the area—included in Appendix A. However, for the weather inputs of erosion model simulations, only event data set is used. Event rainfall data set is used either as original rainfall data or as parametrised rainfall data for erosion estimations.

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 A.1)
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

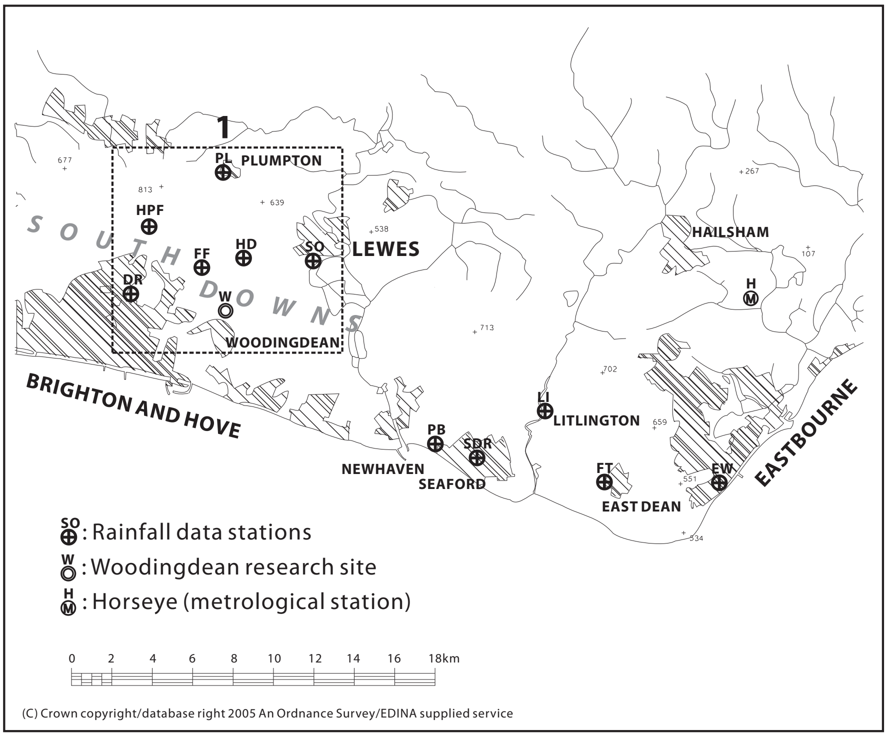


Figure 3.1 Locations of daily rainfall data stations. DR: Ditchling Road, SO: Southover, PL: Plumpton, SDR: Seaford D. Road, EW: Eastbourne Wilm., FT: Friston Tower, LI: Litlington, PB: Poverty Bottom, HPF: High Park Farm, HD: Housedean, FF: Falmer Farm, W: Woodingdean (soil, slope, crop management),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

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.

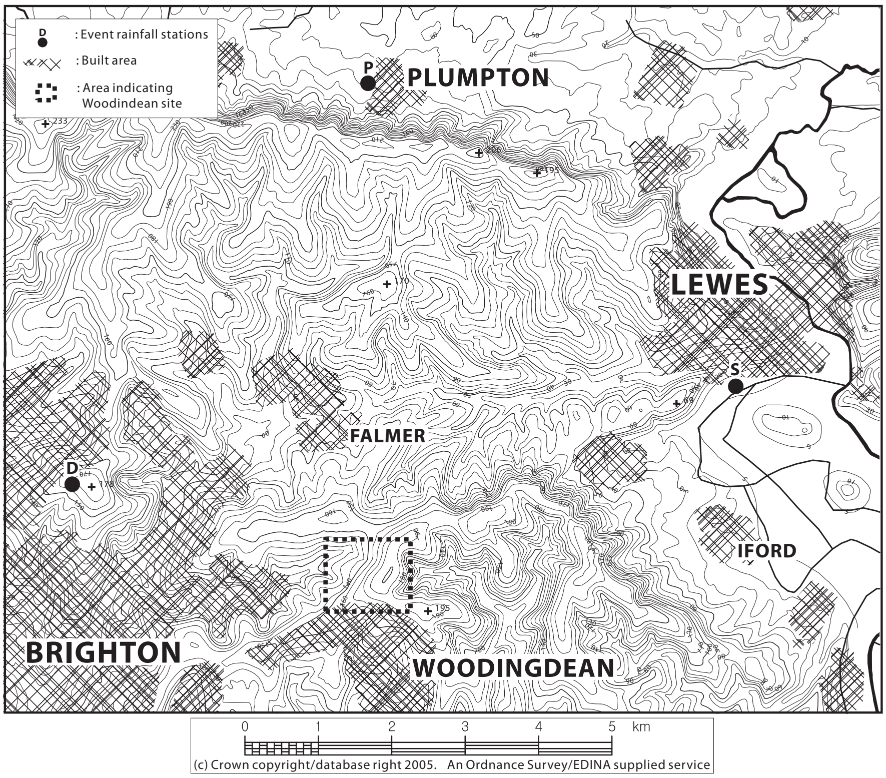


Figure 3.2 Locations of event rainfall data stations. *filled circles*: event rainfall data stations (S: Southover, D: Ditchling Road, P: Plumpton); Woodingdean site is indicated by *dotted frame* (see Figure 3.3 for the detail)

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

Also, a summary of average characteristics of event rainfall data in the area is shown in Table 3.3. Over 75% of the rainfall events that occurred in the area only lasted for less

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

than or equal to 5 minutes.

Table 3.3 Summary of average characteristics of event data

Code	Station	Amount (mm)	Duration† (min)	Intensity‡ (mm/hr)	Max. Intensity‡ (mm/hr)
S	Southover	5.3	24.5	12.8	72
D	Ditchling Road	4.9	22.7	12.8	89
P	Plumpton	7.5	33.9	12.7	28

† "effective" duration without no-rain periods.
‡ Intensity calculated with effective durations.

3.1.3 Other Data

3.1.3.1 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 3.5. 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.

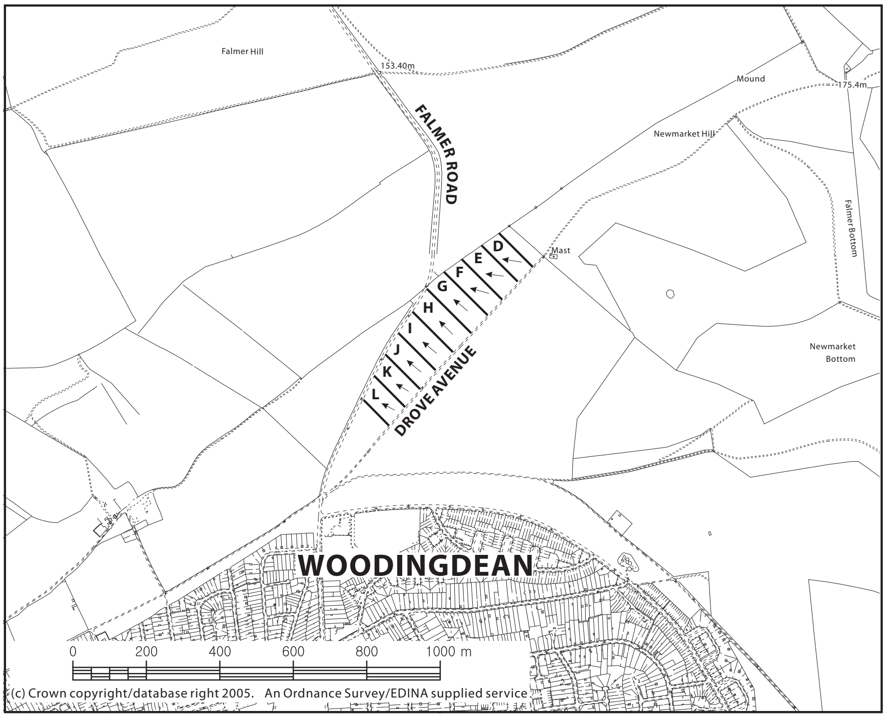


Figure 3.3 Woodingdean site. The arrows indicate approximate downslope direction. Each letter (D-L) denotes hillslope profiles used for model simulations.

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 3.4 and Table 3.5.

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 3.5). The parameters for interrill and rill

Table 3.4 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

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).

Table 3.5 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

3.1.3.2 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 3.6.

Table 3.6 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

3.1.3.3 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.

3.1.3.4 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 3.7).

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 3.7 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.*, 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,

Table 3.7 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*b*	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

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 resolution 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 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 "resolution". 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.

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

Statistical methods used in this research are briefly summarized here.

3.3.1.1 Simple Linear Regression

Linear regression function ($y = \alpha + \beta x$) was assumed where rainfall related indicators (Table A.1) 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.

3.3.1.2 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).

3.3.1.3 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).

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, the 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 respects. The first was the redefinition of an input parameter, 'MX.5P', which controls rainfall intensity generation in CLIGEN. The second was the correction of the unit conversion error in programming codes of CLIGEN. The third is a subsequent adjustment to remedy the resulting unintended increases of simulated rainfall durations.

These changes prompted an investigation of their implications on rainfall generations of CLIGEN and, in turn, soil erosion estimations of WEPP with CLIGEN providing the input weather data. Before using the improved CLIGEN for this research, it is important to understand how the improved CLIGEN performs and simulates weather data in comparison to the previous version. A first reason for this is to gain insight into CLIGEN's operation. A second reason is to see how these changes to CLIGEN affect the conclusions made by previous publications on soil erosion under future climate change. A third reason is that these changes may have invalidated previous sensitivity analyses which involved CLIGEN (Baffaut *et al.*, 1996; Zhang *et al.*, 1996; Baffaut *et al.*, 1998; Favis-Mortlock, 1998*a*; Favis-Mortlock and Guerra, 1999).

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.

4.2 Data Preparation and Method for Model Simulation

Firstly, two CLIGEN input files—original and updated (see Appendix C)—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 4.1) and 'MX.5P' (Table 4.2) values of CLIGEN inputs were recalculated using the up-to-date event data.

[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."

Note that the units for these parameters are in inches, not in millimetres. Only these two parameters were updated. The definition of the 'MX.5P' was revised by Yu (2000) following his discovery of the CLIGEN errors, so it was recalculated accordingly in this research.

Table 4.1 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 4.2 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

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 4.3). These climate data were compared in terms of rainfall amount, duration and peak intensity.

Table 4.3 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

Two combinations of data and CLIGEN (i.e. v4.1+original and v5.2+updated) are of the main concerns in this chapter because the other combinations (i.e. v5.2+orginal and v4.1+updated) have "invalid" combinations of MEAN P and MX.5P. Thus, the latter combinations will not give realistic results. They are only considered here to highlight the changes of CLIGEN as a sensitivity test.

[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.

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. A 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.

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, $p < 0.05$).

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, $p < 0.05$).

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

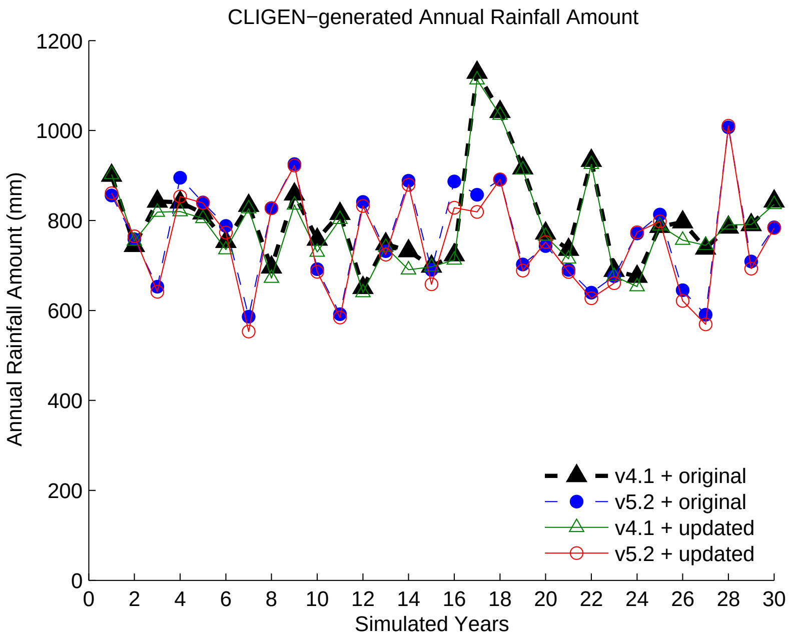


Figure 4.1 Simulated annual rainfall amount using two versions of CLIGEN with original and updated input files.

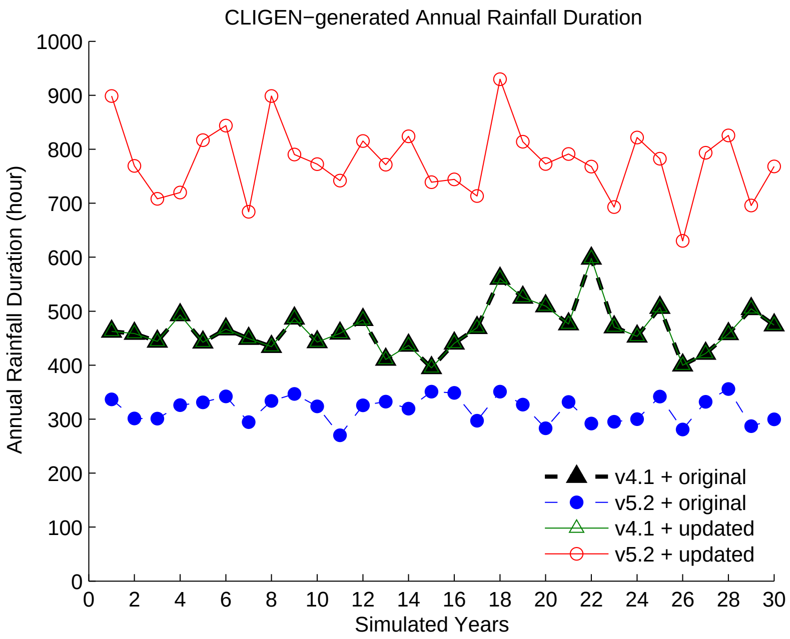


Figure 4.2 Simulated annual rainfall duration using two versions of CLIGEN with original and updated input files.

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. These large differences in rainfall durations mean that rainfall intensities also differ greatly between the simulated rainfall datasets.

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.

The 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 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)). Note that 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 the high peaks are different depending on the version of CLIGEN and input files (Figure 4.3).

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

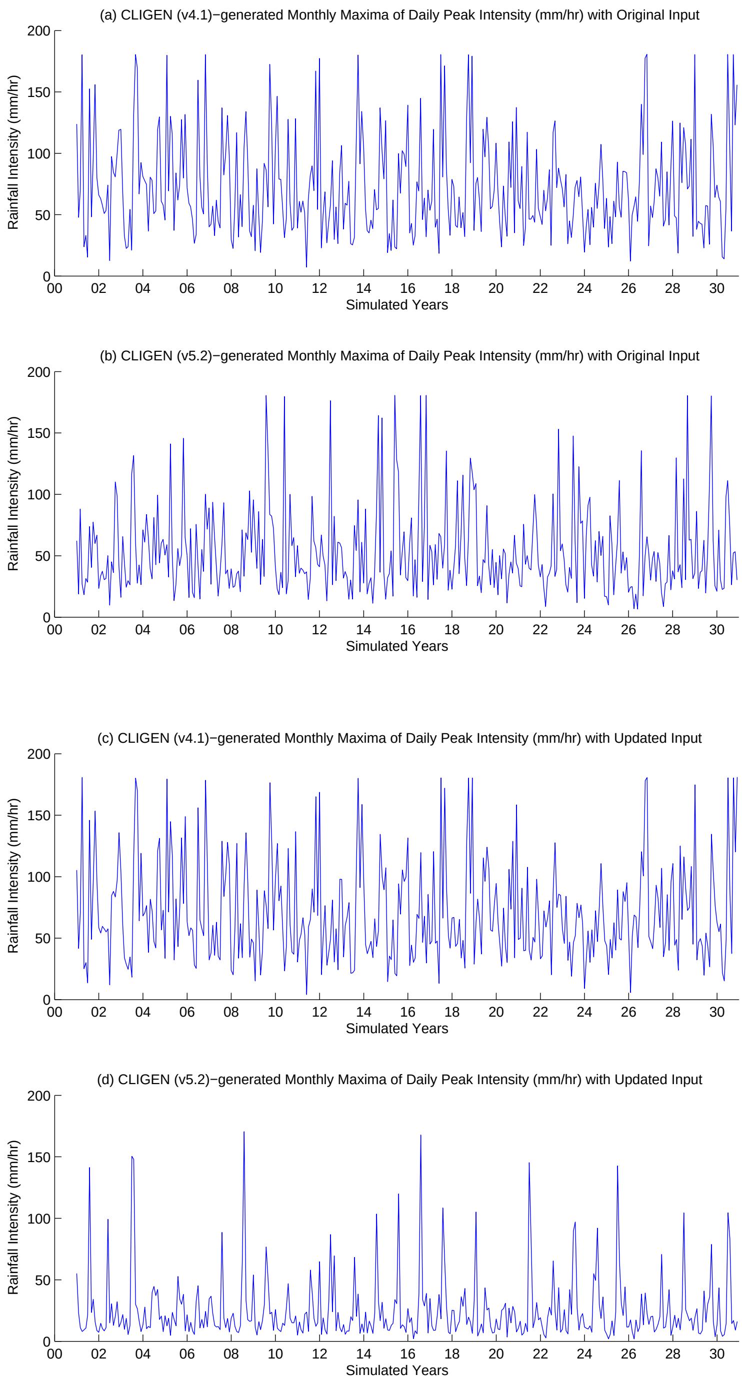


Figure 4.3 Simulated monthly maxima of daily peak rainfall intensity using two versions of CLIGEN with original and updated input files. (a) CLIGEN v4.1 with original input file; (b) CLIGEN v5.2 with original input file; (c) CLIGEN v4.1 with updated input file; (d) CLIGEN v5.2 with updated input file.

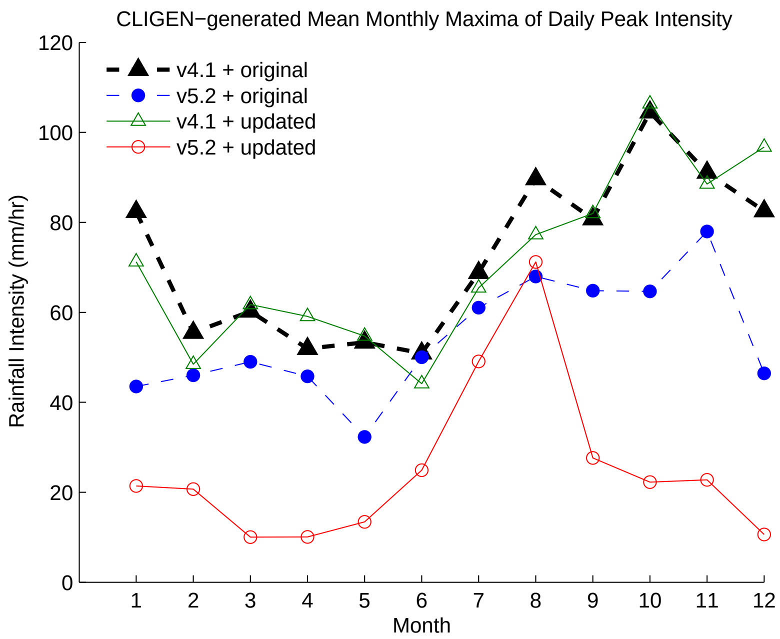


Figure 4.4 CLIGEN-generated mean monthly maxima of daily peak intensity using two versions of CLIGEN with original and updated input files

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 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. In other words, nev CLIGEN with updated input file (v5.2 + updated) simulated more realistic monthly rainfall intensity. This combination (i.e. 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. This result is closely similar to observed rainfall intensity found previously (Figure A.18)

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 unrealistically high for the study site so that calibrations is considered essential.

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*)

Thus, WEPP was calibrated by adjusting hydrological and erosional parameter values. The adjusted parameters were shown in Table 3.5. 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*).

Why Calibrate? 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).

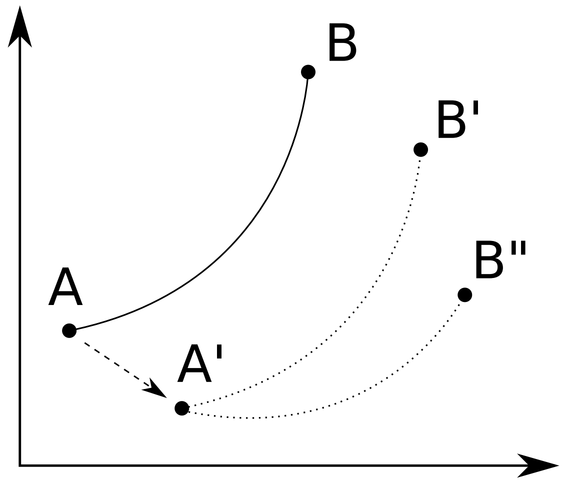


Figure 4.5 A graphical representation of non-linear responses of a erosion model

Then, in order to find possible effects of changes in inputs, 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.

Therefore, it is very unlikely that non-calibrated models will lead to reasonable simulation results. However, even after calibration, there still is the possibility of ending up with 'the right answer for the wrong reason' (Favis-Mortlock, 1994). This is, for example, because two or more model inputs cancel each other out (or enhance each other) by unknown interactions.

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.

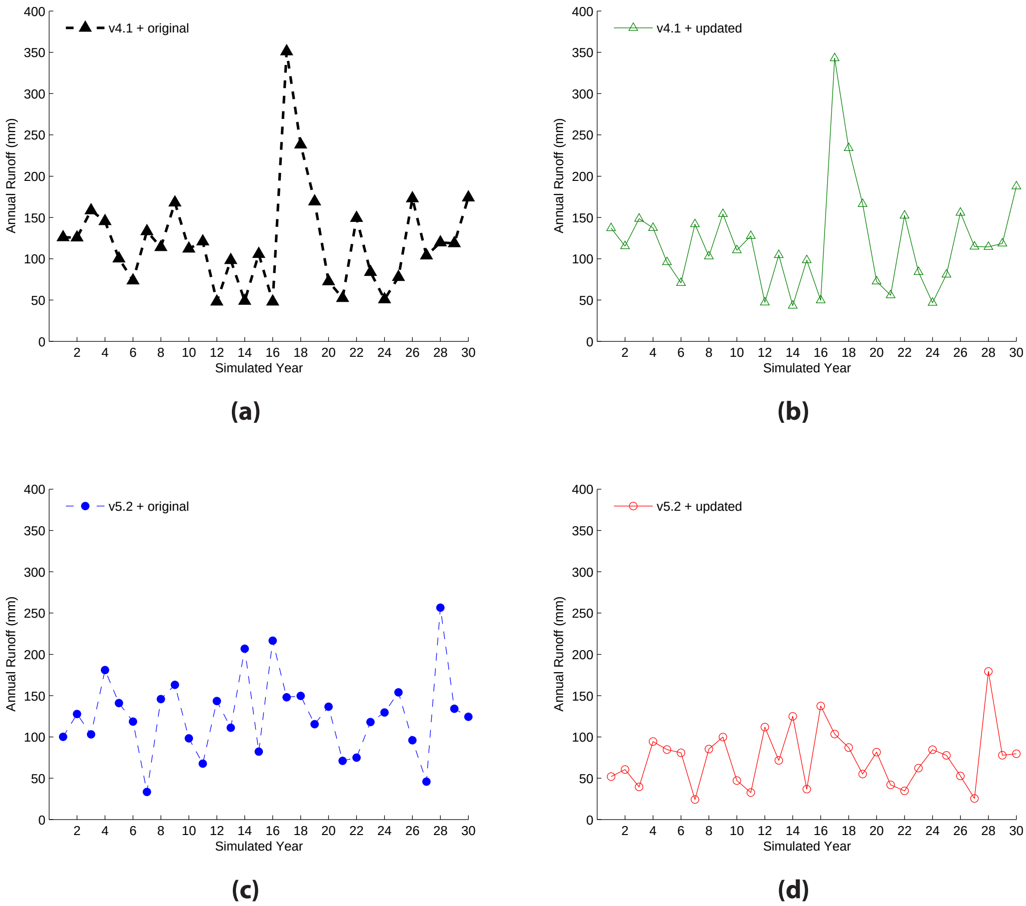


Figure 4.6 Simulated annual runoff for Ditchling Road simulated with (a) old CLIGEN with original input file; (b) old CLIGEN with updated input file; (c) new CLIGEN with original input file; (d) new CLIGEN with updated input file. Note the same Y-axis scale in all plots.

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

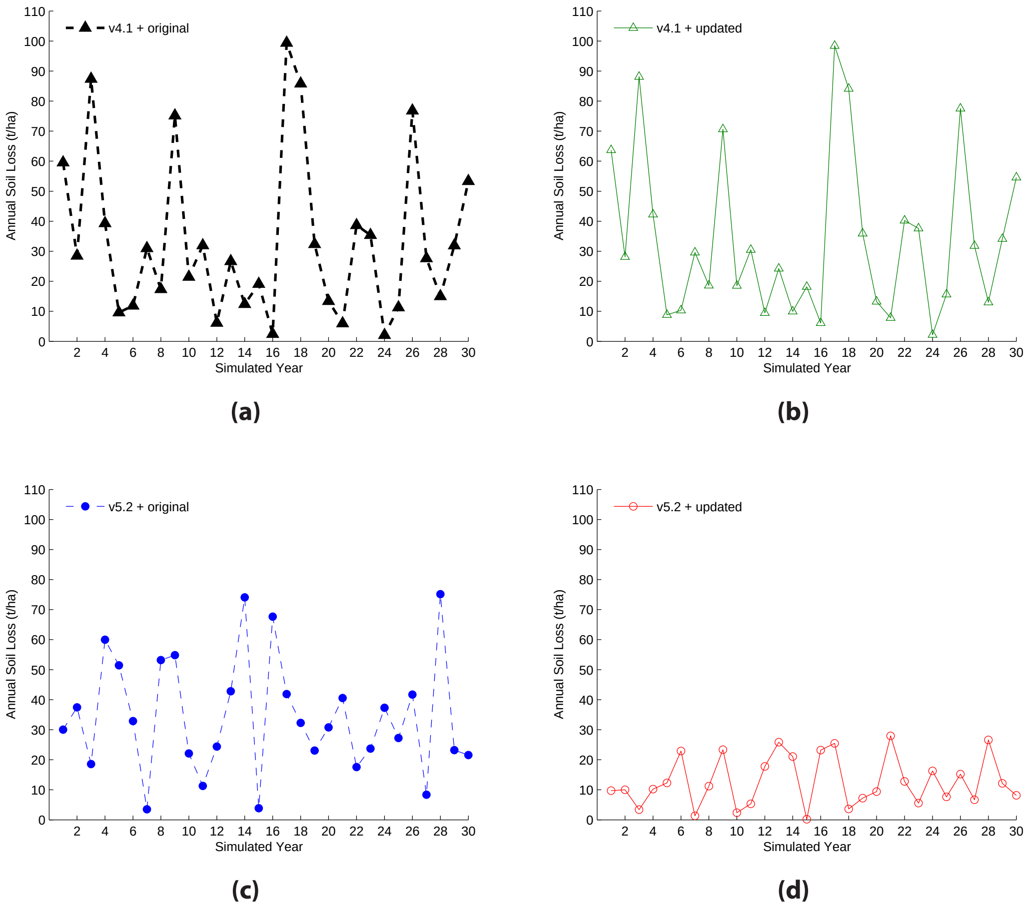


Figure 4.7 Simulated annual soil loss for Ditchling Road simulated with (a) old CLIGEN with original input file; (b) old CLIGEN with updated input file; (c) new CLIGEN with original input file; (d) new CLIGEN with updated input file. Note the same Y-axis scale in all plots.

+ original and v4.1 + updated). However, this is reasonable given that there is little difference in the rainfall amounts and peak rainfall intensities for these combinations (Figure 4.3).

Mean annual runoff and soil loss rates estimated using 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.

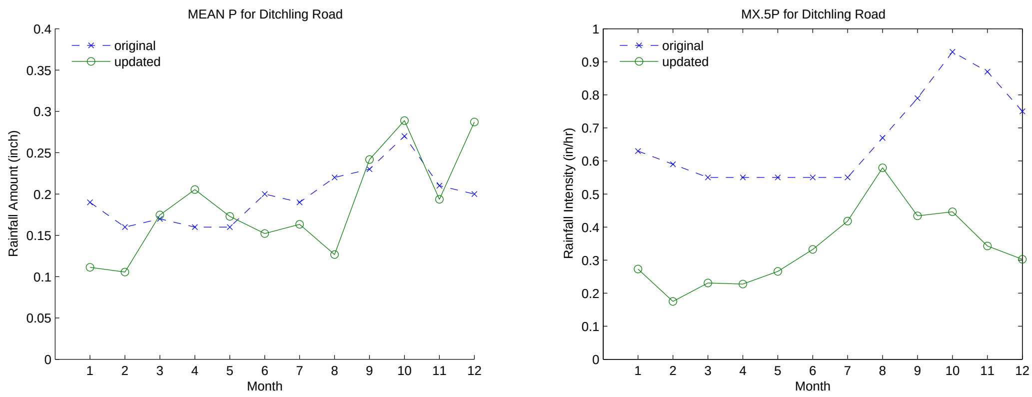
Relative vs Absolute Model Output In this research, both relative (% change) and absolute (t/ha) values were used for model outputs. It may seem more meaningful to use only relative representations (% change) of model outputs than to use absolute values (t/ha) together with % changes because what this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

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 clear 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 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 corresponding 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 smaller impacts on weather generations for locations 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) for all future studies. 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 questionable as average annual soil loss rate was increased even though average annual runoff was decreased.

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

Thus, 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 greatly 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 somewhat.

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 parameterized 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 RESOLUTION OF STORM DATA ON SOIL EROSION

5.1 Introduction

When modelling soil erosion, finding suitable input data for the simulation is an important aspect 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 resolutions 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 resolutions and the location where they are measured from (Nyssen *et al.*, 2005). Consequently, using rainfall data that have a undesired data resolution 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 resolutions 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 a future climate, and that this future climate has different rainfall intensity from the present, what information (both regarding climate, and regarding erosion processes) do we need to make predictions of soil erosion rates under that future climate?

5.2 Data Preparation and Method

Two storms that occurred on 4 July 2000 and on 11 October 2000 were selected from Plumpton event rainfall dataset (P) (Table 3.2). The storm on 11 October 2000 was selected because the rainfall amount of this event was exceptionally high (133.8 mm) for the area and was related to severe erosion and property damage (Boardman, 2001). The return period for such a event is estimated at around 300 years (Saunders *et al.*, 2001). All three stations that record event rainfalls in the region observed a exceptional rainfall on the same day (Figure A.12). However, Plumpton station (P) recorded the highest rainfall amount. This "October" storm was typical of frontal, low-intensity event that occur in winters in South Downs, UK. In comparison, the "July" storm that occurred on 4 July 2000 was selected from the same year in order to increase the diversity of storm patterns that are investigated in this chapter. This storm is typical of summer storm that has a shorter duration than "October" storm (Table 5.1) and has a distinctive high intensity peak in the middle of storm duration. Rainfall amount of this storm also is comparably high and distinctive.

The duration of "October" event was 1208 minutes (i.e. 20 hours and 8 minutes). Average intensity for this rainfall was 6.65 mm/hr with 1-min peak intensity of 84 mm/hr. The "July" rainfall, on the other hand, was recorded with total rainfall amount of 74.8 mm and duration of 808 minutes (i.e. 13 hours and 28 minutes). Average intensity for this event was 5.5 mm/hr with 1-min peak intensity reaching to 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

Tipping-bucket data for both events were aggregated into 5 different temporal resolutions—1, 5, 15, 30 and 60 minutes. This was done to simulate different temporal rainfall data resolution. Each temporal resolution was treated as if it was the "baseline" resolution for the data with these being the only records available. Two sets of temporally varying "July" and "October" storm data were prepared into CLIGEN and breakpoint data format for erosion estimations.

CLIGEN rainfall data describe a rainfall storm 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 temporal data resolution (Table 5.2), and weather inputs for WEPP were built (cf. Appendix B).

Breakpoint data, on the other hand, consist of two parameters: (accumulated) rainfall time and (accumulated) rainfall amounts or intensity. Each dataset was converted into these two parameters, and the number of breakpoints was counted. Breakpoint weather inputs for WEPP are also shown in Appendix B.

Then, two process-based erosion models, WEPP and EUROSEM, are used at the current stage to simulate runoff and soil loss. RillGrow is not used here because of the data resolution and computational time issues involved with using RillGrow. Temporal resolutions that RillGrow simulates with is very small so that it requires a considerably long computational time compared to the duration that is simulated for. To give an idea, RillGrow2 requires almost 7 hours, for example, for running a 45-min simulation (More recent versions of the model are faster, however: David Favis-Mortlock, personal communication, April 2012). This makes using RillGrow for this set of investigations very impractical considering the number of simulations and the total duration of computational time required. Thus, only two models, WEPP and EUROSEM, are used in this chapter.

CLIGEN data and breakpoint data prepared from rainfall data with 1, 5, 15, 30 and 60-min temporal resolution were used for the simulations to investigate the effect of different temporal resolution. EUROSEM was designed to use only breakpoint rainfall data so that it would be a good comparison to WEPP which has been originally designed to use CLIGEN data as well as breakpoint data.

As pointed out, EUROSEM uses breakpoint rainfall data only. This means that, unless the EUROSEM code was rewritten, using CLIGEN data directly with EUROSEM is not possible. Rewriting of EUROSEM code would not be viable for the scope of this research. Thus, 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 ten breakpoints using a double exponential equation before calculating erosion related parameters (see Flanagan and Nearing, 1995, §2.2). These disaggregated breakpoint data can be found in one of WEPP output files. For EUROSEM simulations, these breakpoint data from WEPP outputs were used in place of CLIGEN data. This makes the rainfall data used for WEPP and EUROSEM essentially the same for both simulations (Figure 5.1).

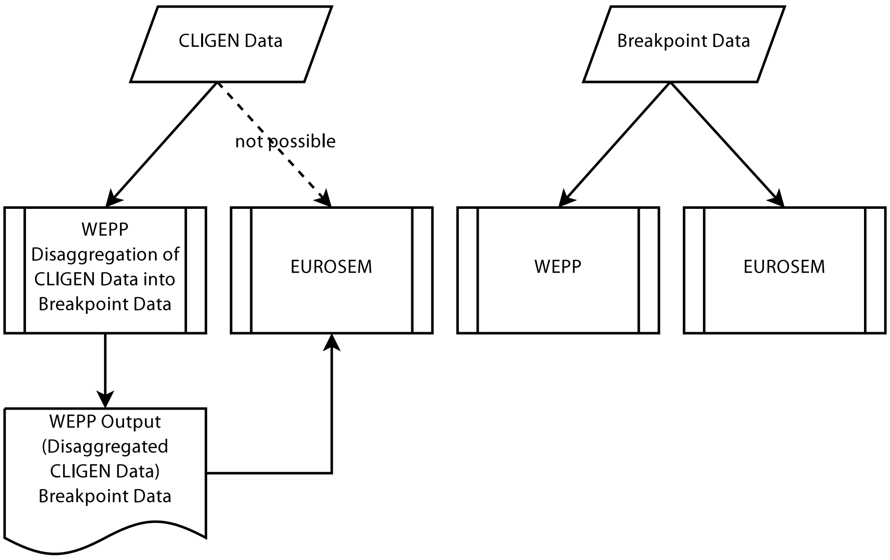


Figure 5.1 A diagram of WEPP and EUROSEM simulations with CLIGEN and breakpoint data

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 again that the emphasis of this research is not on assessing the performance of models against measured data.

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

5.3 Effect on Rainfall Intensity Information

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

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

As shown is Table 5.2, each set of temporally varying rainfall data shows different total rainfall durations. This is because the size of their time intervals are different so that the total number of time intervals are different. For example, if there is rainfall lasted for two 1-min intervals long, total duration becomes 2 minutes. However, for the same rainfall, if we increase time intervals to 60-min, total duration becomes 60 minutes because those two 1-min intervals are included in one 60-min interval. Therefore, effective rainfall duration increases as temporal data resolution increases. With rainfall amounts remaining the same, the changes in duration mean that rainfall intensity information is also affected by the temporal resolution of rainfall data. Peak rainfall intensities are affected by the data resolution too. Moreover, the change of temporal resolution shifts the temporal location of peak intensity (t_p). This means that the effective shape of a storm may change from, for example, ascending intensity to descending intensity. Effects of storm shapes on soil erosion are further investigated in Chapter 7.

Table 5.3 Number of time intervals (breakpoints) for each temporal resolution

Temporal resolution (min)	1	5	15	30	60
4 July 2000	315	135	55	30	16
11 October 2000	460	152	63	35	19
Max. no. of intervals (per day)	1440	288	96	48	24

For breakpoint data, the maximum numbers of time intervals per day as well as the number of breakpoints for each storm are shown in Figure 5.3. The number of breakpoints for the storms decreases as the temporal resolution increases. Also, the rainfall data with different temporal resolutions show different rainfall intensity information (Figure 5.2 and 5.3). Higher temporal resolution data show higher instantaneous peak rainfall intensities. With 1-min data of the "October" storm, for example, a peak rainfall intensity was over 80 mm/hr (Figure 5.3a). In comparison, 60-min data of the "October" storm show no peak rainfall intensity higher than 20 mm/hr (Figure 5.3e). 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 resolution depending on which two bins (i.e. breakpoints) added together and averaged (Figure 5.2 and 5.3).

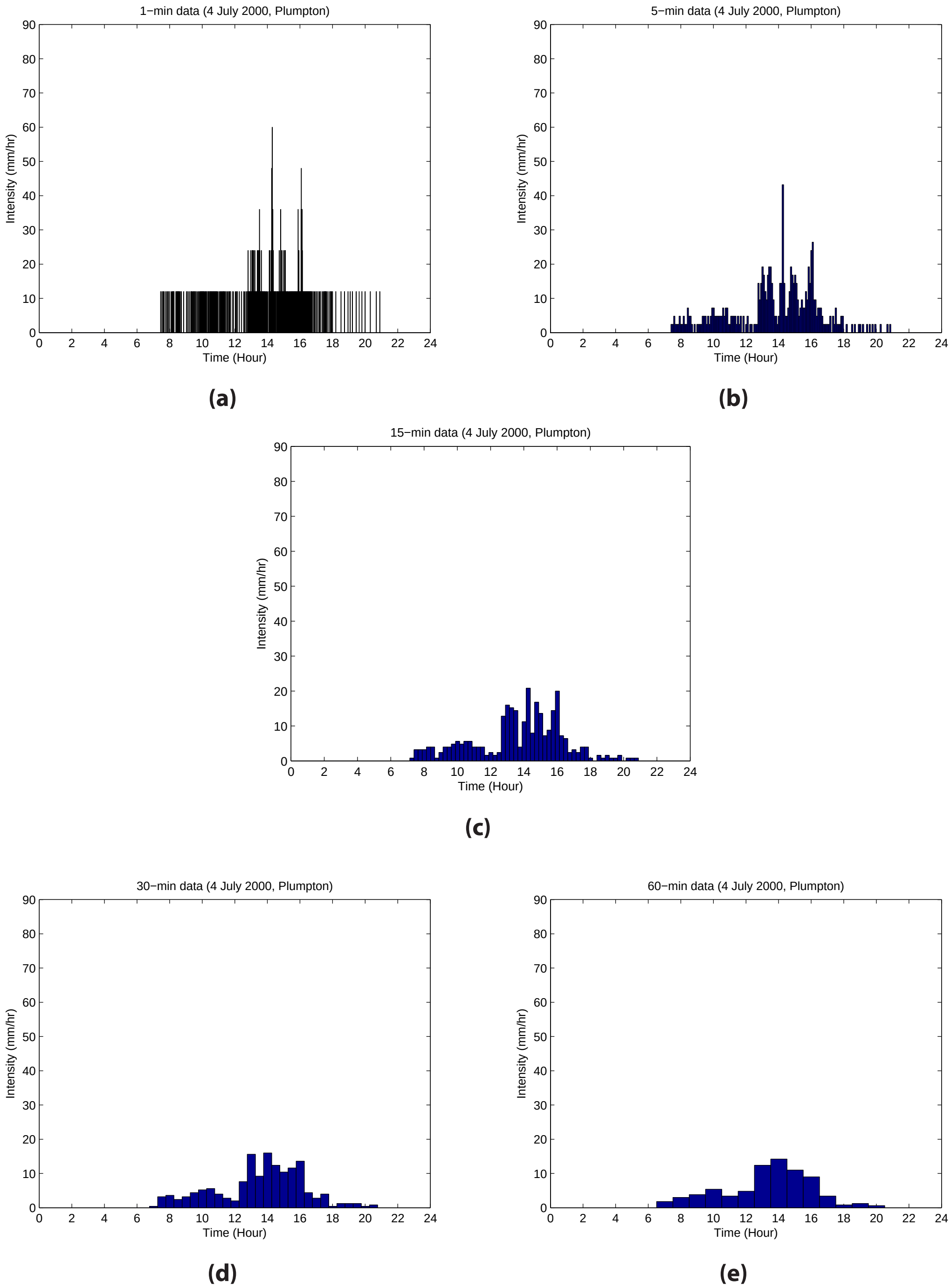


Figure 5.2 Various temporal resolutions of original breakpoint data for 4 July 2000 storm in Plumpton

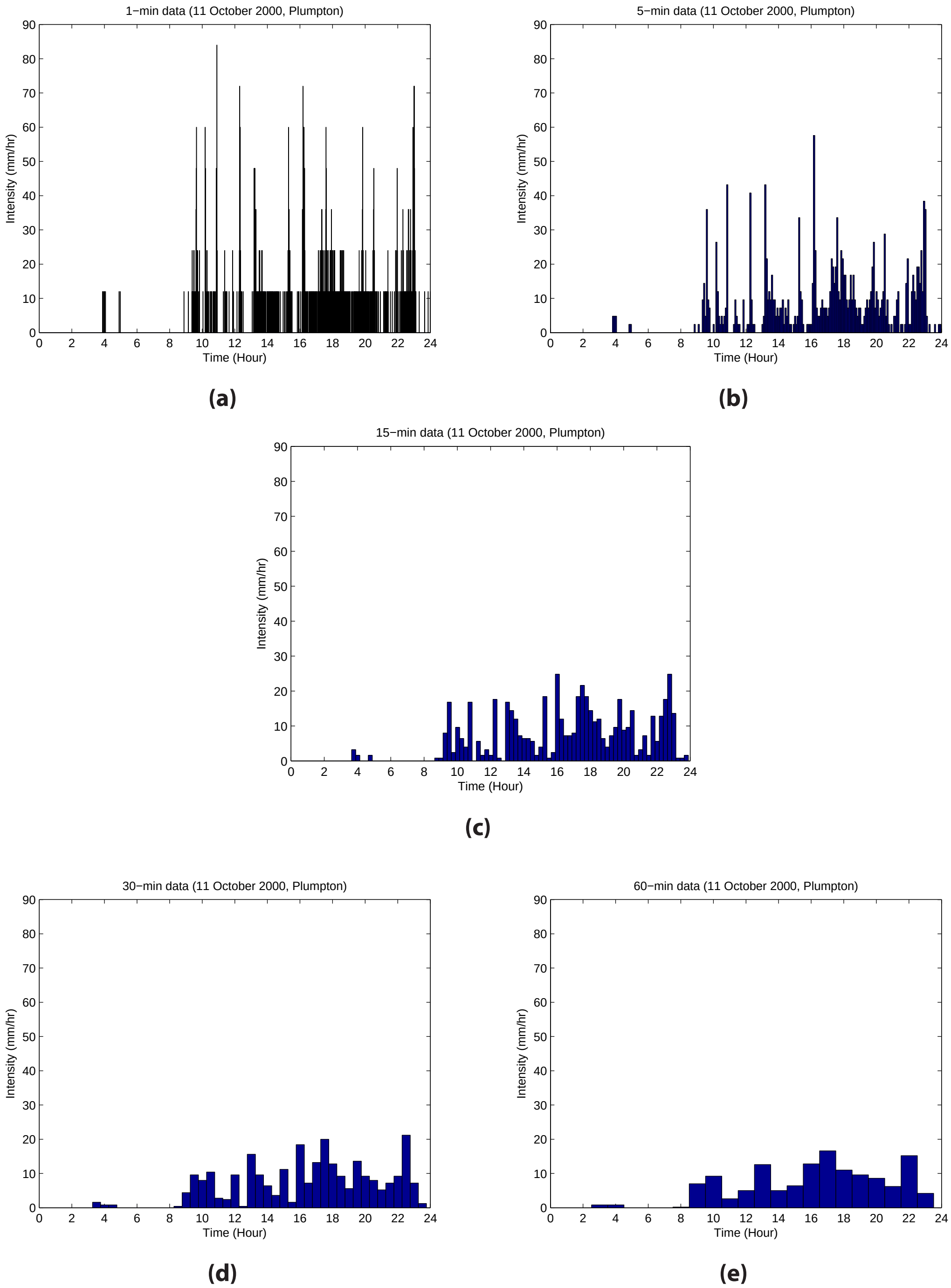


Figure 5.3 Various temporal resolutions of original breakpoint data for 11 October 2000 storm in Plumpton

5.4 Effect 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 WEPP and EUROSEM because of model limitations. During investigation, it was found that WEPP and EUROSEM limits the total number of breakpoints that they can process (Flanagan and Livingston, 1995; Morgan *et al.*, 1998*a*). These limitations are discussed further later in the chapter. Thus, no runoff and soil loss rates were estimated with 1 and 5-min breakpoint data. Instead, CLIGEN data with 1 to 60-min resolutions and breakpoint data with 15 to 60-min resolutions were used to estimate runoff and soil loss rates.

5.4.1 Effect of Temporal resolution on Runoff

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

Runoff amounts estimated by WEPP with CLIGEN and breakpoint rainfall data for each temporal resolution are shown in Table 5.4. Results from WEPP simulations show that the changes of runoff rates from the runoff rates simulated with 15-min CLIGEN data are greater when simulated with 1-min CLIGEN data than with 5-min CLIGEN data. For example, using 1-min data instead of 15-min data of "July" storm resulted in about 45% increase in runoff and 30% increases for "October" storm (Table 5.4). Using 60-min data, on the other hand, of the same storms results in about 20% and 10% decreases in runoff amounts compared to using 15-min data, respectively (Table 5.4). The effect of changes of temporal resolutions are greater when CLIGEN data of the July event are used than the October event.

Table 5.4 WEPP-estimated runoff (mm) with different temporal resolutions of CLIGEN and breakpoint rainfall data

		Temporal Resolution				
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.

Table 5.5 EUROSEM-estimated runoff (mm) with different temporal resolutions of CLIGEN and breakpoint rainfall data

		Temporal Resolution				
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.

When breakpoint data are used, the opposite is observed—the magnitude of the changes are greater for the October event even though these changes are in increasing trends as temporal resolution decreases. In other words, WEPP-simulated runoff rates are greater when 30 or 60-min breakpoint data of the October event are used than when 15-min breakpoint data of the same storm are used. For the July event, decreases in runoff are observed when breakpoint data with the same temporal resolutions (i.e. 30 or 60-min) are used. Also, the magnitude of changes in simulated runoff rates from 15-min data resolution are slightly greater for 60-min data resolution than for 30-min data resolution. Despite these contrasting responses, changing temporal resolutions of breakpoint data for both rainfall events resulted in changes of WEPP runoff generations.

Runoff results generated by EUROSEM for CLIGEN and breakpoint rainfall data with each temporal resolution are shown in Table 5.5. Runoff results from EUROSEM simulations show closely similar results to those from the WEPP simulation. Particularly, when CLIGEN data are used, increases and decreases of runoff rates as well as the magnitude of changes in runoff rates depending on temporal resolutions of the data show the same tenancy as WEPP simulations: The higher the temporal resolution is used, the greater the effect is. Also, simulations with breakpoint data of the October storm show the corresponding results to WEPP simulations which show increased runoff rates for the coarser temporal resolution. However, when breakpoint data of the July storm are used, EUROSEM interestingly generates over 11% greater runoff rate with 60-min resolution than with 15-min resolution while still generating the downward change in runoff rate with 30-min resolution (Table 5.5).

5.4.2 Effect of Temporal Resolution on Soil Loss

Soil loss results generated by WEPP with CLIGEN and breakpoint rainfall data for the different time resolutions are shown in Table 5.6. WEPP estimates greater soil loss rates with high temporal resolutions and lesser soil loss rates with coarse temporal resolutions than with 15-min temporal resolution—with one exception of 30-min breakpoint data of the October storm. Soil loss is increased almost 20% when 30-min breakpoint data of the October storm are used in comparison to when 15-min breakpoint data of the storm are used.

For WEPP simulations, soil loss rates are affected more dramatically by the change of temporal resolutions than runoff rates. For example, with 1-min CLIGEN data of the July event, WEPP estimates almost a 300% increase in soil loss rate and almost a 90% decrease with 60-min CLIGEN data for the same event in comparison to the estimation result with 15-min CLIGEN data (Table 5.6). The effect of changes in temporal resolution for the breakpoint data of July storm is also similar to the change patterns with the CLIGEN data which is inversely proportional to the temporal resolution. However, 30-min breakpoint data of the October storm show the opposite result that is almost 20% increase in soil loss rate compared to 15-min breakpoint data while 60-min breakpoint data for the same event result in an over 55% decrease in soil loss.

Table 5.6 WEPP-estimated soil loss (t/ha) with different temporal resolutions of CLIGEN and breakpoint rainfall data

		Temporal Resolution (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 with CLIGEN and breakpoint rainfall data for each temporal resolution are shown in Table 5.7. The result of simulations using EUROSEM shows unanticipated responses to the changes of temporal resolutions. Except soil loss rates estimated with 5-min CLIGEN data, all soil loss rates estimated

Table 5.7 EUROSEM-estimated soil loss (t/ha) with different temporal resolutions of CLIGEN and breakpoint rainfall data

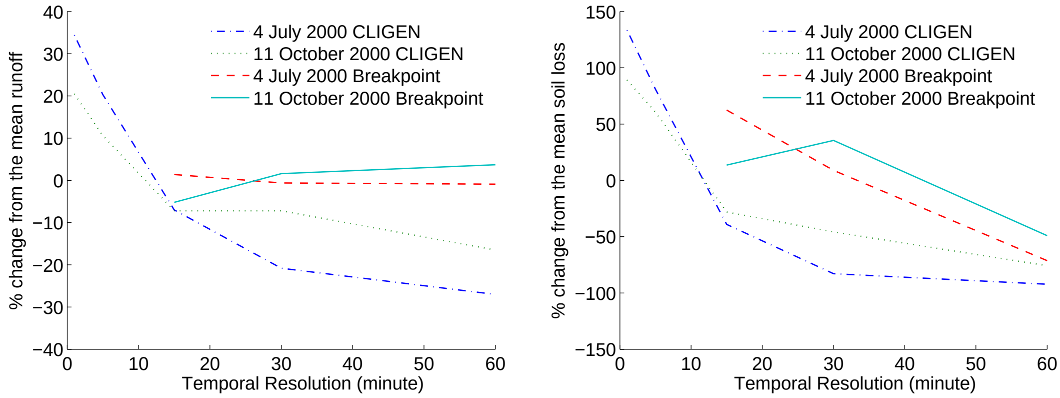
		Temporal Resolution (minutes)				
Data type	Event	1	5	15	30	60
CLIGEN	4 Jul 2000	13.0 (+26.2)	10.0 (−2.9)	10.3	10.7 (+3.9)	10.9 (+5.8)
	11 Oct 2000	24.7 (+5.6)	21.5 (−8.1)	23.4	23.8 (+1.7)	25.4 (+8.6)
Breakpoint	4 Jul 2000	–	–	10.0	10.2 (+2.0)	12.0 (+20.0)
	11 Oct 2000	–	–	19.4	21.9 (+12.9)	23.3 (+20.1)

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

with CLIGEN data are increased from the rates estimated with 15-min data (Table 5.7). This means that, with an exception of 1-min CLIGEN data, the simulation results of soil loss rates do not correspond to the runoff rates estimated by EUROSEM with CLIGEN data (Table 5.5). EUROSEM estimates increases in soil loss while estimating decreases in runoff when 30 and 60-min resolutions of CLIGEN data are used. Also, decreases in soil loss are estimated while increases in runoff are estimated with 5-min resolution of CLIGEN data. For breakpoint data, the effect of changes in temporal data resolution on soil loss rates is almost—except for the 30-min breakpoint data of "July" storm—consistent with the effect on runoff rates simulated by EUROSEM with breakpoint data.

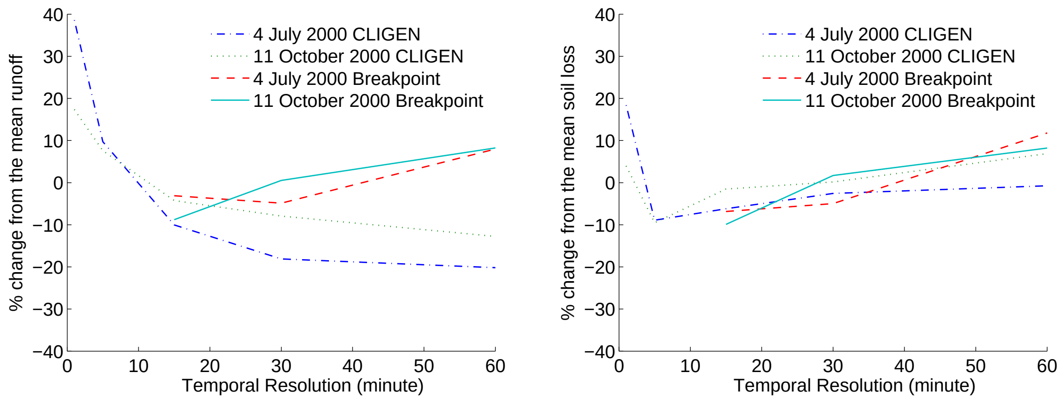
The changes (%) from the mean values of runoff and soil loss simulated by WEPP and EUROSEM are also plotted in Figures 5.4 and 5.5, respectively. These figures show overall responses of runoff and soil loss rates to the changes of temporal data resolution.

Changes of temporal resolutions of CLIGEN rainfall data are inversely proportional to WEPP-simulated runoff and erosion rates (Figure 5.4). CLIGEN data with higher temporal resolutions (i.e. 1-min and 5-min resolutions) resulted in greater WEPP-simulated runoff and erosion rate than CLIGEN data with lower temporal resolutions (30-min and 60-min resolutions). For breakpoint data, temporal data resolutions have a varying effects on WEPP-simulated runoff and erosion rates and do not show clear correlations with the simulation result (Figure 5.4).



(a) Runoff **(b)** Soil Loss

Figure 5.4 The changes of WEPP-simulated runoff and soil loss from average runoff and soil loss. Note the different scale of y-axis in (b) Soil Loss.



(a) Runoff **(b)** Soil Loss

Figure 5.5 The changes of EUROSEM-simulated runoff and soil loss from average runoff and soil loss

Temporal data resolutions also have certain effects on runoff and erosion rates simulated by EUROSEM as seen in Figure 5.5. However, EUROSEM-simulated erosion rates show rather different results from results of WEPP simulations. Results of EUROSEM simulations for erosion rates are mostly the opposite from WEPP simulations with some exceptions. Using CLIGEN data generally resulted in decreasing runoff and increasing soil loss rates as temporal resolutions increase. This is rather unexpected because decreasing runoff rates are normally accompanied by decreasing soil erosion rates. Also, 1-min CLIGEN data is the only temporal resolution that show increasing soil loss rates as well as increasing runoff rates (Figure 5.5). For breakpoint data, changes of temporal resolutions resulted in a moderate increasing trend in both runoff and erosion rates. However, the correlation is rather weak because of the lack of data points to consider.

5.5 Discussion

Although WEPP documents states that 15-min data are to be used (Flanagan and Livingston, 1995), 15-min data are not always available for the erosion modelling studies. Thus, the effect of other temporal resolutions have been investigated. The results were compared against those of 15-min data and average values of runoff and soil loss in terms of the rates of changes (%) to highlight the relative effects of the changes.

Maximum number of breakpoints As mentioned previously, breakpoint data that were prepared for both July and October events with 1-min and 5-min data could not be used for WEPP and EUROSEM. This was because WEPP have a limit on the maximum number of breakpoint which is 50 points per day according to the model document (see Flanagan and Livingston, 1995, page 10). This means that, for a rainfall event that lasts for a whole day, for example, 30-min data is the highest resolution we can use for WEPP simulations because there are only 48 (24 hr/0.5 hr) intervals available per day. This prohibits the use of breakpoint data with temporal resolution higher than 30-min in theory. In practice, any temporal resolution could be used as long as the total number of breakpoints does not exceed 50 points. For example, for a storm that lasts 50 mins, and if that storm is the only rain on that day, temporal resolution could be 1 minutes.

WEPP was developed for the US (Flanagan *et al.*, 2007). In the US mid-west, the whole of a day's rain may arrive in one rather short (with relatively high intensity) storm. Thus, this limitation (of ≦ 50 breakpoints) is not so severe in the US. However, for places where it may rain for a whole day, where rain may arrive in long, low-intensity storms like South Downs, UK, this ≦ 50 breakpoints limitation is a definite problem.

Testing with WEPP (v2004.7) revealed that up to 100 breakpoints may be used without a problem. However, when the number of breakpoints exceeds 100 points, WEPP does not recognise the start and end of a rainfall event correctly, and re-aggregates the rainfall with multiple starting points (i.e. 0 minute point). Thus, the maximum number of breakpoints it can handle should be increased to at least 1440 points or more to enable the use of 1-min data or higher temporal data—that is, when daily event is assumed. EUROSEM have the same limitation which prevent from using more than 100 breakpoints. When tested with more than 100 breakpoints, EUROSEM simply does not yield any meaningful output. Also, EUROSEM has a limit on the total number of time increments which should not be more than 1000 per simulation (Morgan *et al.*, 1998*a*). This may cause more difficulties when a storm with an extensively long duration is used for detailed simulations. Therefore, both models need to increase their dimension of breakpoint data array to meet the need.

WEPP vs EUROSEM In terms of soil loss rates estimated by two models, WEPP exhibited greater responses than EUROSEM to the changes of temporal data resolutions. Although EUROSEM was not as much sensitive as WEPP to the temporal resolution of rainfall data, it showed some responses to the temporal resolution changes. The biggest change, which was 26.2 %, in soil erosion estimations was observed when 1-min CLIGEN data were used (Table 5.7). In comparison to the WEPP's response (i.e. 283.2 %) for the same CLIGEN data, the change was considerably small (Table 5.6). Even with breakpoint data, 20.1 % change for 60-min breakpoint data was the largest change for EUROSEM (Table 5.7). Again, WEPP estimated 55.2 % change for the same breakpoint data (Table 5.6).

Moreover, EUROSEM results for CLIGEN data were contradictory to the physical process of soil erosion. As shown previously, EUROSEM generated increased soil loss when runoff was decreased (Figure 5.5).

Table 5.8 Summary of detailed EUROSEM outputs estimated with CLIGEN data

		Temporal Resolution (min)				
Output	Event	1	5	15	30	60
Gross Rill Erosion (t/ha)	04 July 2000	10.4	8.8	10.3	10.7	10.9
	11 October 2000	17.5	16.9	23.4	24.1	25.6
Gross Interrill Erosion (t/ha)	04 July 2000	2.8	1.2	0.011	0.009	0.008
	11 October 2000	7	4.6	0.028	0.024	0.02
Net Erosion (t/ha)	04 July 2000	13	10	10.3	10.7	10.9
	11 October 2000	24.7	21.5	23.4	23.8	25.4
Net Rainfall (mm)	04 July 2000	73.9	73.9	73.9	73.9	73.9
	11 October 2000	132.9	132.9	132.9	132.9	132.9
Rain Duration (min)	04 July 2000	312	666	798	840	840
	11 October 2000	444	768	930	1020	1080
Peak Intensity (mm/h)	04 July 2000	55.9	40.5	19.7	14.7	13.5
	11 October 2000	79.4	54.6	22.8	19.5	15.7
Runoff Duration (min)	04 July 2000	199	210	336	415	451
	11 October 2000	433	355	704	656	848
Peak Runoff Rate (mm/h)	04 July 2000	51.7	35.5	15.8	11.1	10.1
	11 October 2000	73.3	51.8	19.8	16.8	12.8
Time to Peak Runoff (min)	04 July 2000	202	389	444	461	473
	11 October 2000	63	359	459	936	722
Infiltration (mm)	04 July 2000	20.2	31.9	39.5	42.5	43.4
	11 October 2000	31.2	40	50.3	52.7	57.5
Runoff (mm)	04 July 2000	53.5	42.1	34.6	31.5	30.7
	11 October 2000	102.1	93.6	83.3	80.1	75.9

A close examination of EUROSEM model outputs revealed that the estimated amount of “Gross Interrill Eroison” was substantially greater for 1 and 5-min CLIGEN data than for 15, 30 and 60-min CLIGEN data (Table 5.8) while the amount of “Net Erosion Rate” was roughly the same. This means that smaller amounts of “Gross Rill Erosion” were estimated for 1 and 5-min data resolutions than for the bigger temporal resolutions. Thus, it seems that there is a certain change in the way that EUROSEM calculates rill and interrill erosion rates when the temporal resolution of data changes from 15-min to 5-min and vise versa. As reviewed previously in Chapter 1 (see page 37), the model document indicated that EUROSEM uses separate transport capacity relationships for rill and interrill flows: Govers (1990) for rill transport capacity and Everaert (1991) for interrill transport capacity. The same is true for WEPP too as rill and interrill erosion are calculated using separate erodibility parameters (Flanagan and Nearing, 1995). However, in EUROSEM, one seems to play more important role than the other on overall erosion depending on the surface condition:

- The surface may contain no rills, but have some surface irregularities

  → Interrill erosion is simulated with a high proportion of the soil surface covered by shallow overland flow.

- The surface may be rilled, with interrill flows routed toward the rills

  → both shallow flow between rills and downslope flow with bigger carrying capacities are simulated.

- The surface may be furrowed, or have very dense rills, such that interrill routing is illogical due to the short distance traversed by interrill flows

  → “overbank” flow is considered. The two areas (i.e. rill and interrill) are connected as surface elevations become equal. The unified rill profile model can be used.

The EUROSEM model document also stated that EUROSEM uses a dynamic approach for estimating the spatial temporal distribution of runoff and soil loss (Morgan *et al.*, 1998*a*).

Therefore, when temporal resolution of rainfall data changes from 15-min to 5-min, the slope surface condition, which EUROSEM simulates, seems to shift from the third condition to the second condition from the list above. Then, EUROSEM changes its simulation mode so that interrill erosion becomes accounted for. This explains why the relatively large interrill erosion was estimated for 1 and 5-min resolutions. Thus, it could be suggested that the transition of the simulation mode occurs somewhere between 5-min and 15-min of temporal resolutions.

Yet, reasons for the disagreement between runoff and soil loss rate can not be explained by this "mode-shifting" as well as the reduction of net erosion for 5-min data. An in-depth investigation could be suggested to explain this finding fully as a follow-up study after this research.

CLIGEN vs Breakpoint data Rainfall parameters in the CLIGEN input file were originally calculated from 15-min breakpoint data. CLIGEN then used this statistical information to simulate continuous long-term daily rainfall data, which have similar statistical characteristics as the observed data, or individual storm data could be manually calculated to be in the form of four unique parameters: rainfall amount, rainfall duration, normalised peak intensity and normalised time to peak. These four parameters were then used by WEPP to disaggregate the daily rainfall data into ten breakpoint data using a double exponential function.

In total, original breakpoint data had gone through two parametrisation processes effectively. Thus, this procedure of "parametrisation and disaggregation" seems 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 occurred on 11 October 2000. The rainfall information can be distorted and lost during these data "parametrisation and disaggregation" processes.

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.

One reason why WEPP-CLIGEN use such method seems to be because of the ease of use and data storage for long-term rainfall 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 dependent.

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 easy to use with WEPP as it is designed specifically for this purpose.

If only two extreme ends of the resolution are considered from the result shown previously in Table 5.6 and 5.7, for example, between 1-min and 60-min CLIGEN data, simulated erosion rates with 1-min data are almost 30 times greater at most than those with 60-min data. This certainly is problematic as far as the effect of temporal resolutions of rainfall data on erosion rates is concerned.

Also, when erosion rates estimated with 15-min and 60-min breakpoint data are compared, erosion rates with 15-min data is over 5 times greater at most than those with 60-min data. Again, a greater difference is observed when erosion rates estimated with CLIGEN data for the same temporal resolutions are compared. Erosion rates with 15-min CLIGEN data are 7.5 times greater at most than those with 60-min CLIGEN data.

Therefore, breakpoint data generally produce smaller changes in erosion rates when temporal resolutions are changed. This however is not conclusive by any means because the responses of two models (i.e. WEPP and EUROSEM) are rather contradictory for both CLIGEN and breakpoint data in terms of their trends of increases or decreases.

Data aggregation and rainfall intensity The intensity information of rainfall data is heavily dependent 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 dependent on the start time as well as time-steps which is temporal resolutions. 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 rainfall events—i.e. 4 July 2000 and 11 October 2000—were aggregated into varying time steps. Distinctive high intensity peaks in 1-min data (Figures 5.2a and 5.3a) was no more visible because intensities were averaged out over the longer time-steps (cf. Figures 5.2e and 5.3e).

Effect of temporal resolution changes Two effects can be noted when temporal resolution increases. One is that it lowers of the actual instantaneous peak intensity and average intensity of rainfall storms. The other is that it changes the location of peak intensities during storm durations.

Lowering the average intensity means a reduced average power of erodibility of the rain. Also, lowering the peak intensity means a reduced instantaneous peak power of erodibility of the the rain. These reductions in erodibilities may be a significant reason for the underestimation of the runoff and soil loss generations. Equally, the opposite can be expected when temporal resolution decreases. Some of these responses are observed in this chapter (see Figures 5.4 and 5.5).

Shifting the location of the peak rainfall intensity can occur when temporal resolutions are changed regardless of increase or decrease. Also, the placement of the peak intensity do not seem to be related to the direction of changes (see Table 5.2 and Figures 5.2–5.3). However, When the location of the peak intensity changes, it too changes rainfall shapes (or patterns) which may be closely related to the timing of the runoff generations and amount of the runoff (This is further investigated and discussed later in Chapter 7.). Thus, changes in temporal resolutions of rainfall data affect the shape of rainfall storm.

All these changes—lowering of intensities and shifting the location of peak intensities—will of course occur simultaneously when the temporal resolution of rainfall data is altered. Thus, what we observed in this chapter may well be the end product from compound effects of these two changes. Effects of lowering of intensities and shifting the location of peak intensities on runoff and soil loss rates therefore need to be investigated separately to be understood further.

Within-Storm Intensity Variation (WSIV) The variation of rainfall intensities within a storm could be termed as Within-Storm Intensity Variation (WSIV) for convenience. WSIV may include the magnitude and number of peak intensities and average intensity of a storm. As suggested previously, WSIV is related to temporal resolutions of rainfall data as well as types of storms (e.g. convective and frontal). WSIV changes when rainfall intensities are decreased (or increased) by increasing (or decreasing) temporal resolutions of rainfall data.

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 resolution in rainfall is a significant factor in controlling the resolution-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 into a manageable data format may let important rainfall intensity details to be missed out as shown in this chapter.

Boardman and Spivey (1987) also pointed out that short period high intensities probably important for soil erosion processes. However, short duration rainfall intensities are subject to 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).

Thus, high temporal resolution data are needed in order to describe WSIVs of storms realistically. High temporal resolution data can provide great details of WSIVs including high instantaneous intensity peaks. However, high resolution data even as sub-hourly data are very rarely available. As Allott *et al.* (2002) pointed out, rainfall data with high resolutions permit a more detailed assessment of the storm structure and evolution of localised intense storms, but storms are rarely stored by sub-hourly.

Even though storms are often originally recorded as sub-hourly data by tipping-bucket gauges, the original records are rarely kept as they are. Instead, they are usually aggregated into hourly or daily data for data storage. Thus, only hourly or daily data are available in many cases. Therefore, a little is ever known about the storm structure, evolution and, of course, WSIVs. With hourly (or more generally daily) data, the detail of actual rainfall intensity can not be obtained. This has been shown previously by comparing Figure 5.3a and Figure 5.3e, for example. The differences in WSIVs between hourly data and 1-min data may have been particularly responsible for the great dissimilarities in runoff and soil loss rates between two temporal resolutions.

Therefore, it is evident that temporal resolutions of rainfall data play a crucial role in runoff and soil loss modelling. Changes of temporal resolutions affect the amount of details on WSIVs which, in turn, affect runoff and soil loss estimations. Sub-hourly data hold more details of WSIVs than hourly data. Thus, it would be logical to choose sub-hourly data over hourly data (i.e. 60-min resolution) for erosion modelling. Also, because breakpoint data are less affected by the changes of temporal resolutions than CLIGEN data, breakpoint data can be preferred to CLIGEN data. In addition, breakpoint data maintains the detail of WSIV better.

Among the investigated sub-hourly resolutions, 1-min and 5-min resolutions of breakpoint data cannot be used, however, because WEPP and EUROSEM have the limited number of rainfall data points they can handle. Now there are only two choices left: 15-min and 30-min breakpoint data. There could be other sub-hourly resolutions available, for example, 10-min, 20-min and so on. However, these other sub-hourly resolutions were not considered here because investigations were only carried out with the ones used in this chapter: 1, 5, 15, 30 and 60-min. Therefore, within the temporal resolutions investigated in this chapter, 15-min data were chosen. This temporal resolution will be used for the subsequent analyses in this research because they have greater details of WSIVs than 30-min data. Moreover, WEPP and EUROSEM can easily use 15-min breakpoint data.

It is also recognised that different ways of expressing rainfall intensity have the tenancy of desirability for erosion modelling. This is summarised in Table 5.9.

Table 5.9 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 resolution of breakpoint data limits their closeness to real rainfall since rainfall intensity is averaged between starting and ending time of breakpoints.

Lastly, it is important to note again that a erosion model should be able to take high resolution data such as 1-min breakpoint data. Once this limitation is resolved, other sub-hourly data resolutions may also become available for the similar investigation conducted in this chapter. This, in turn, extend the findings presented in this research.

5.6 Conclusion

This set of investigations evidently showed that temporal resolution of rainfall data have certain impacts on runoff and soil loss estimations. However, it could not answer if rainfall data with a high resolution always give better simulation results than rainfall data with a low resolution. This is because there are no measured runoff and soil loss rates to compare. Despite the absence of the measured data to be compared with, this chapter identifies the close relationship between temporal resolutions and WSIVs of rainfall data. When temporal resolutions of rainfall data increase (or decrease), rainfall intensities are decreased (or increased). WSIVs are also changed when rainfall intensities of storms change.

If there are no available high resolution data but only low resolution data (e.g. 60-min data), we will never know what the intensity was like during those 60 minutes because the disaggregation of rainfall data is no plausible. Also, simulation results can be up to about 30 times different from the "original results" if these low resolution data are used. This magnitude is so great that it might mean from almost no erosion to disastrous events.

In this chapter, the following was found:

- Temporal resolutions of rainfall data affect Within-Storm Intensity Variations (WSIVs)
- Temporal resolutions of rainfall data are closely related to the estimated results of runoff and soil loss
- In terms of soil loss, WEPP is more sensitive to the change of temporal data resolutions than EUROSEM

- Erosion estimations with CLIGEN data are more affected by the change of temporal resolutions than those with breakpoint data
- Breakpoint data are preferred to CLIGEN data as far as investigations on effects of rainfall intensity on erosion are concerned
- For the subsequent analyses of this research, 15-min breakpoint rainfall data are chosen

As stated previously, this chapter is followed by a further investigation which aims to answer the research question: '*What is the consequence of removing the no-rain periods within a storm duration?*'. The removal of no-rain periods—that is later termed as Within-Storm Gaps (WSGs)—is required during CLIGEN data preparation processes. However, it raises a concern that the removal of WSGs may lead to a loss of rainfall intensity information. More worryingly, a distortion of rainfall patterns and feeding this wrong information into soil erosion models could also occur. In the next chapter, therefore, effects of WSGs on soil erosion estimations are investigated.

Chapter 6

EFFECT OF CONTINUOUS AND DISCONTINUOUS STORM ON SOIL EROSION

6.1 Introduction

As indicated previously (see page 32), effective rainfall duration (D, minute), which is one of four parameters that describe rainfall characteristics in CLIGEN data, is calculated by discarding no-rain periods within storm duration. Only rainfall periods within storm duration are aggregated into a "gapless" rainfall storm. By removing no-rain periods, actual rainfall duration is reduced so that average intensity of rainfall storm is increased. Consequently, the removal of no-rain periods, which is termed as Within-Storm Gaps (WSGs) for this research, may have effects on erosion modelling.

Therefore, this chapter examines the effect of the removal of WSGs on runoff and soil loss estimations. Continuous (without WSGs) and discontinuous (with WSGs) storms are distinguished by the existence of WSGs within the storm duration. Three process-based models—WEPP, EUROSEM and an additional model, RillGrow—were used in this chapter. Runoff and soil loss rate were estimated by these models and the outputs were examined in terms of their relationships to WSGs.

WEPP and EUROSEM have shown contrasting results in the previous chapter. Thus, RillGrow was used here with an intention to strengthen the model estimation results by increasing the number of model predictions. Although the outputs from three erosion models may still give three very different results—this actually was the case—employing all three models may also give a stronger argument that the removal of WSGs does (or does not) have an impact on runoff and soil loss simulations. The main aim of this investigation is to find out whether WSGs influence runoff and soil loss generations. The more important question is, however, how WSGs influence runoff and soil erosion. This is more difficult to answer even when a single erosion model is used.

6.2 Simulation Data and Methods

Event rainfall recorded on 11 October 2000 at Southover station (S) (see Table 3.2) was selected because this event was a distinctive storm with a large amount of rainfall. The event also includes a number of WSGs in the total storm duration. The total rainfall amount of the storm is 89.9 mm. This event is considered to be responsible for the severe flood incidents in the study region (Boardman, 2001).

Only breakpoint data type, which retains WSGs, was used in this chapter because CLIGEN data remove WSGs by its design specification. Also, temporal resolution of 15-min was used as discussed in the previous chapter, Chapter 5. Hyetographs of the original rainfall event and the modified rainfall event, in which WSGs are removed, are shown in Figure 6.1. The rainfall intensities for each 15-min interval were maintained

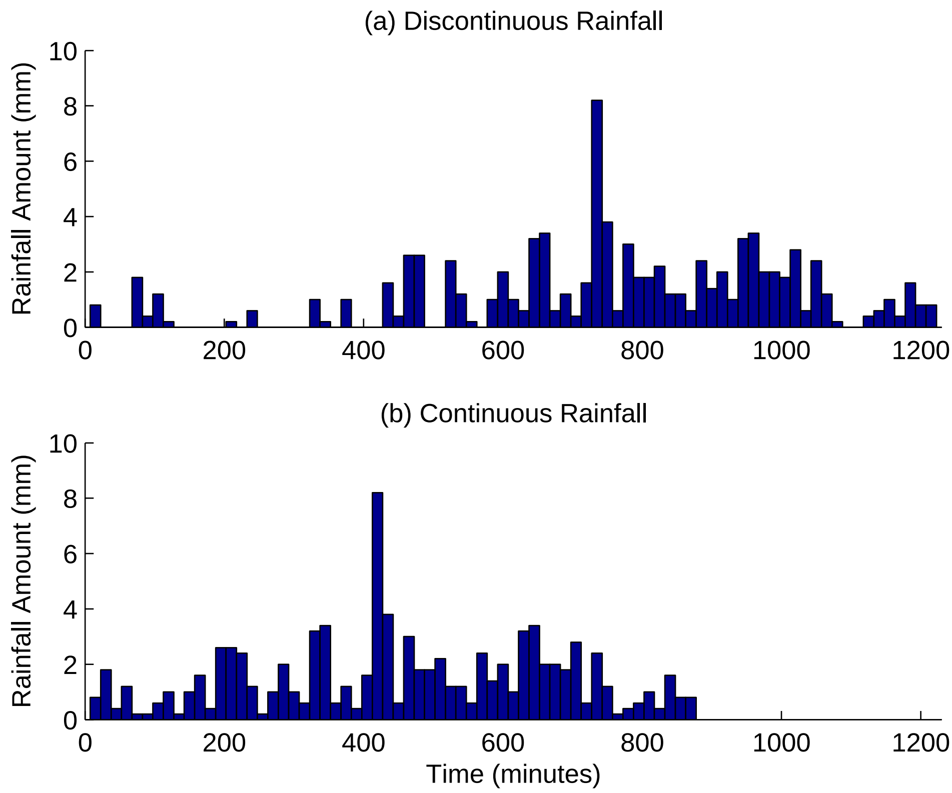
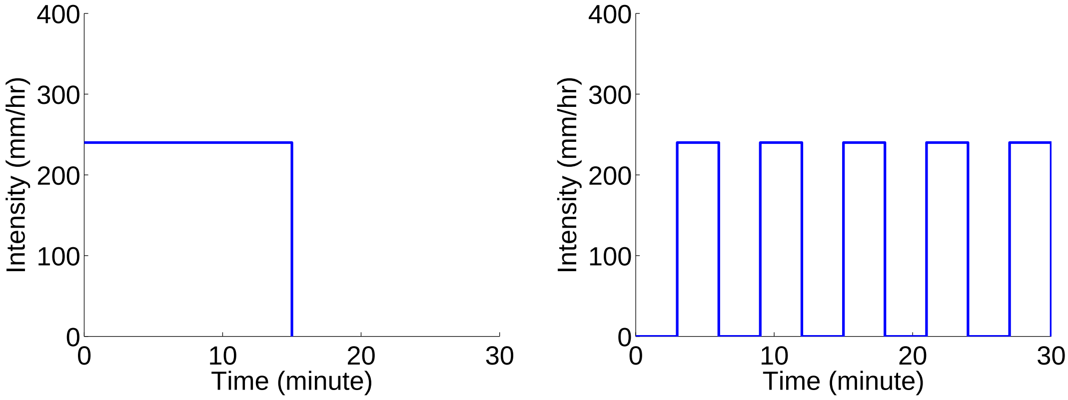


Figure 6.1 15-min rainfall data used for the investigations of effects of continuous and discontinuous rainfall on soil erosion. (a) original 11 October 2000 event ;(b) modified 11 October 2000 event after removing WSGs

the same (Figure 6.1). Total duration of the data with WSGs was 1230 minutes and 885 minutes without WSGs.

Then, WEPP and EUROSEM were used to simulate runoff and soil loss using these breakpoint data.

A separate set of continuous and discontinuous rainfall data were prepared for RillGrow simulations. Because RillGrow simulates runoff and soil loss in great detail temporally and spatially, a rainfall event with a relatively short duration—to reduce computational time—and a number of high intensity peaks with a constant intensity were intentionally prepared (Figure 6.2). For this designed storm, constant intensity was used because it made the shape of the storm simple. Also, it minimises any unforeseen



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

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.

modelling interference from the changes of WSIV.

Simulated runoff and soil loss rates by WEPP, EUROSEM and RillGrow using the prepared rainfall data are presented in the next section.

6.3 Simulation Results

WEPP simulation result WEPP-estimated runoff amounts for continuous and discontinuous rainfalls are shown in Table 6.1. WEPP generated less runoff with discontinuous rainfall than with continuous rainfall. WEPP-estimated runoff decreased 10 percent when estimated with a discontinuous rainfall than with a continuous rainfall. However, for soil loss, WEPP estimated more soil loss with discontinuous rainfall than with continuous rainfall. The soil loss estimated by WEPP increased 4.6 percent with discontinuous storm in comparison to the soil loss rate with continuous storm.

EUROSEM simulation result EUROSEM-estimated runoff and soil loss rates for continuous and discontinuous rainfall are shown in Table 6.2. EUROSEM generated a lesser amount of runoff with discontinuous rainfall than with continuous rainfall.

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.

Also, less soil loss was estimated by EUROSEM with discontinuous rainfall than with continuous rainfall. Runoff and soil loss rates estimated by EUROSEM decreased 11.9 and 12.7 percent, respectively, with discontinuous storm in comparison to those 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 simulation result RillGrow-estimated soil loss rates for continuous and discontinuous rainfall are shown in Table 6.3. RillGrow generated slightly more runoff with discontinuous rainfall than that with continuous rainfall. With discontinuous rainfall, runoff increased 0.2 percent in comparison to runoff estimated with continuous rainfall. The simulated runoff amounts were in fact almost the same. This is because no infiltration was considered during the simulation. Thus, every rain ran off the edge of the simulated plot. The infiltration component of RillGrow2 was inactive. The current version of RillGrow, which is version 6, has resolved the problem and has a working infiltration component (personal communication with the developer, D. Favis-Mortlock, on 31 January 2012).

Yet RillGrow estimated slightly less soil loss with discontinuous rainfall than with continuous rainfall. The soil loss rate was decreased one percent with the discontinuous storm in comparison to the soil loss rate with the continuous storm.

Despite the changes in runoff and soil loss, magnitudes of the change were much smaller than changes observed in the 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)

† Because of the model output parameter, total volumes of runoff was presented in litre. Figures in ( ) are the % changes from the result with a continuous storm.

6.4 Discussion

Breakpoint or CLIGEN data Using breakpoint data for a erosion simulation prevents the loss of WSG information from the original data. Therefore, it is reasonable to choose breakpoint data over CLIGEN data for studies similar to the current research which investigates effects of rainfall intensity changes on soil erosion in great detail. However, using breakpoint data for continuous long-term simulation, for example, is realistically almost impractical since preparing such inputs for erosion modelling is a very labour intensive and tedious task. Regardless to say that temporally high resolution data may well not be always available for a long period too. Thus, for some cases, CLIGEN data, which removes WSGs from original rainfall data, are inevitably chosen for erosion modelling studies. This investigation showed the effect of removing WSGs during rainfall duration on erosion simulations.

Effect of removing WSGs on EUROSEM results By removing WSGs, we are unintentionally creating a rainfall event with higher average intensity than the original average intensity as total storm duration becomes shortened. This means that, first of all, the time given for the erosion simulation is decreased so that smaller values of time-related parameters such as runoff duration are used for other relevant process calculations. This will have an effect on, for example, the time allowed for runoff initiation and development. Secondly, the increased average intensity may increase on the erosional power of rain storm. Thus, amounts of soil detachment and soil particles carried away by surface flow could be increased. Depending on the dominant process, runoff and soil loss could increase or decrease together.

Removing WSGs during a storm duration may result in, for example, increased runoff and soil loss rates in comparison to those simulated with the original rainfall because of increased erosive power of storm being more dominant than the time reduced. This seemingly was the case for EUROSEM simulations (Table 6.2).

EUROSEM showed significant impacts of WSGs on estimated runoff and soil loss. By maintaining WSGs, runoff was simulated with almost 12% smaller amount than by removing WSGs. This reduction in runoff was corresponded with decreased soil loss which was almost 13% smaller than that of continuous storm. These results imply that if runoff and soil loss are estimated by EUROSEM, the result could vary over 10% depending the existence of WSGs in breakpoint data. This figure, of course, may well be specific to the storm that have been used here. In order to find a more general magnitude of the impact, a further investigation may be needed. Also, the relationship between magnitudes of changes and proportions of WSGs in storms may need to be investigated. Nevertheless, even without any further test, it is clear that WSGs do have impacts on EUROSEM-estimated runoff and soil loss. WEPP and RillGrow showed rather different results from the EUROSEM results, however.

RillGrow without infiltration component First of all, simulation results from RillGrow runs showed very small differences between continuous and discontinuous rainfall. In fact, the differences in runoff and soil loss between two rainfalls were almost negligible. This, as mentioned previously, could have been the result of the infiltration component not having been activated in RillGrow. Thus, infiltration was not considered for the RillGrow simulations.

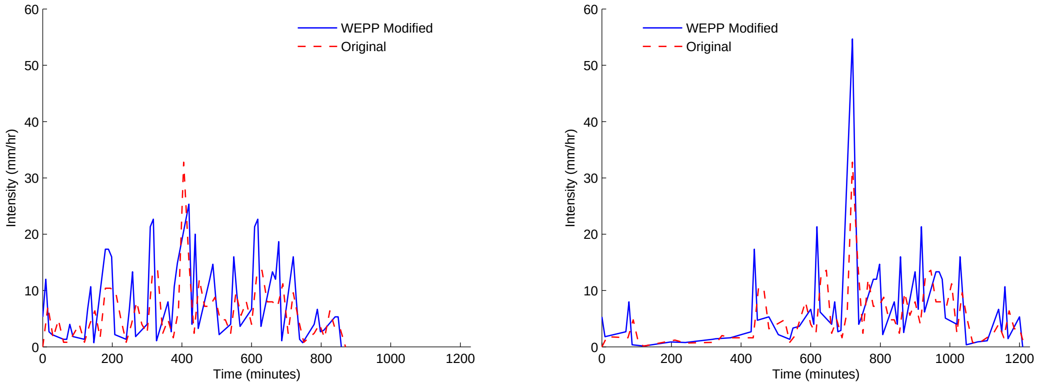
In comparison to RillGrow, however, the other two models, which have working infiltration components, showed some degrees of changes in runoff and soil loss. This implies that infiltration component plays an important role in making the differences in the simulated runoff and soil loss rates. Thus, without the working infiltration component, RillGrow2—the version of RillGrow that was used in this investigation—was assumed to be not sensitive to WSGs.

The more improved version of RillGrow, which is in version 6, has functioning infiltration component (personal communication with D. Favis-Mortlock in December 2011).

Modification of original breakpoint data by WEPP WEPP estimated more soil loss with discontinuous rainfall than with continuous rainfall even though runoff was decreased when simulated with discontinuous rainfall. This was unexpected. If average rainfall intensity of a rainfall storm is increased keeping the amount unchanged, the increased average intensity is expected to produce more runoff and, in turn, more soil loss than low average intensity. However, the opposite results were observed from the WEPP simulation result.

By examining WEPP outputs thoroughly—including the WEPP outputs from the previous chapter, Chapter 5, it was found that WEPP actually misinterpreted the intensity of the original breakpoint data, and modified the original intensity information before using them for estimating runoff and soil loss.

WEPP reconstructed a "new" rainfall storm based on the original breakpoint data when the temporal resolution of rainfall data shorter than an hour were used. This "WEPP-modified" rainfall storm had the same accumulated rainfall amounts and the number of breakpoints from the original data, but the time increments for each data point were changed. By changing the original time increments, WEPP, in effect, changed the original rainfall intensity information. The differences between the original breakpoint data and the "WEPP-modified" breakpoint data are illustrated in Figure 6.3. WEPP decreased intensity peaks of continuous rainfall while it increased intensity peaks of continuous rainfall as seen in Figure 6.3.



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

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

The peak intensity of continuous rainfall was decreased from 32.8 mm/hr to 25.3 mm/hr (Table 6.4). This is about a 23% decrease in the peak intensity. The rainfall amount and total duration of continuous rainfall were kept almost the same so that the average rainfall intensity for the original data and WEPP-modified data were almost the same (Table 6.4). Also, the peak intensity of discontinuous rainfall was increased from 32.8 mm/hr to 54.7 mm/hr (Table 6.4). The peak intensity was increased about 67%. Since the rainfall amount and total duration of discontinuous rainfall were kept almost the same too, the average rainfall intensity for the original data and WEPP modified data were almost the same. These details are summarised in Table 6.4.

Table 6.4 Detailed summary of original and wepp-interpreted storm intensity (mm/hr)

	Continuous		Discontinuous	
	Peak	Average	Peak	Average
Original	32.8	6.2	32.8	4.4
Wepp-interpreted	25.3	6.3	54.7	4.5
Change (%)	-22.9		+66.8	

+/- denotes increase or decrease

This finding poses a serious problem and, as far as only WEPP (with breakpoint data) is concerned, has a substantial impact on our ability to investigate impacts of rainfall intensity changes not only in the future but also in the present. Without ability to process original intensity information, it is very likely to end up with invalid results similar to the WEPP simulation result shown in this chapter (see Table 6.1).

6.5 Conclusion

Within-Storm Gaps (WSGs) have impacts on runoff and soil erosion simulated by WEPP and EUROSEM except RillGrow. RillGrow showed almost no changes in runoff and soil erosion simulation results because of the lack of functioning infiltration component. Although it was not evident whether WSGs had positive or negative effects on runoff and soil erosion estimations, removing WSGs from original rainfall data affected the model simulation results. Thus, it is not recommended to remove WSGs from the original rainfall data in order to maintain the original rainfall intensity information. It is a best practice to use rainfall data which have all necessary information for modelling.

Analyses of outputs from WEPP simulations revealed a new problem. WEPP modified original rainfall intensity information and simulated erroneous results (Table 6.1. This is because that WEPP constructs a "WEPP-modified" rainfall data based on original rainfall data when breakpoint data with a temporal resolution shorter than

60-min temporal resolution is used for WEPP simulations. Particularly, peak rainfall intensity and the shapes of rainfall storm are altered. This clearly is a major problem for current research and for our ability to predict erosion. This is also 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, which WEPP actually uses for the simulation, have different rainfall intensity from the original data. This then leads to the estimation of unrealistic soil erosion.

Chapter 7

EFFECT OF WITHIN-STORM RAINFALL INTENSITY PATTERN ON SOIL EROSION

7.1 Introduction

In the last two chapters, the effect of temporal resolutions and WSGs on soil erosion have been investigated. In Chapter 5, first of all, it was shown that time-to-peak intensity (t_p) was affected by temporal resolution of rainfall data. When time-to-peak intensity changes, overall shape of rainfall storm, which can be termed as Within-Storm Intensity Pattern (WSIP), changes together. For example, when a peak intensity occurs at the later stage of a storm, WSIP becomes a skewed triangular shape towards the end of rainfall duration (cf. Figure 7.2a). As suggested previously, time-to-peak may have an impact on erosion estimations. Thus, WSIP may too have impacts on runoff initiation as well as soil loss amount.

Secondly, in Chapter 6 (see page 124), it was pointed out that WEPP changed WSIVs when modified the original rainfall intensity information. WSIVs are closely related to WSIP. For example, when "rainfall intensity" within a storm increases steadily from low to high (i.e. increasing intensity), WSIP becomes a skewed triangular shape towards the end of rainfall duration (cf. Figure 7.2a). The same principle applies to decreasing or constant, or more complex shapes. In addition, the change of WSIP may occur when WSGs are removed from original rainfall data as previously illustrated in Figure 6.1.

Therefore, this chapter investigates the effect of rainfall intensity changes (i.e. WSIVs) within storm duration in terms of WSIP by using WEPP, EUROSEM and RillGrow. In reality, rainfall intensity is constantly changing throughout the storm period. It may increase or decrease and changes in more complex ways. For the modelling purpose, however, design storms are used in this chapter. This is because design storms are easier to compare with each other without any additional data preparation. Also, by using design storms, it is easier to isolate a factor that is of interest without changing other factors.

7.2 Simulation Data and Methods

Rainfall storms with varying WSIP—increasing, decreasing, increasing-decreasing and constant—are constructed as CLIGEN data by changing time-to-peak (t_p) values. The constant WSIP are achieved by setting both t_p and i_p to 1.0. Amounts of these rainfalls are also kept the same. In order to investigate only effects of WSIP changes on erosion estimation. Only one peak intensity (or no peak for the constant intensity) per storm is assumed for model simulations because of WEPP requirements.

Two designed storms with average intensity of 10 mm/hr (120 mm for 12 hr, Figure 7.1) and 60 mm/hr (120 mm for 2 hr, Figure 7.2) are prepared for WEPP and EUROSEM simulations . Two different intensities are used here in order to investigate effects of WSIP changes in storms with low and high rainfall intensities. Intensity of 10 mm/hr is selected because it is approximately the same as the average intensity (12.8 mm/hr) of the rainfall storm that occurs in the study area, South Downs, UK (see page 202, Chapter 3). Also, the higher intensity (i.e. 60 mm/hr) is selected because it is approximately the same level as the average maximum intensity (63 mm/hr) in the study area (see page 202, Chapter 3).

Firstly, for WEPP simulations, these two rainfall data are used as CLIGEN data format. Then, as described previously in Chapter 5 (see Figure 5.1, page 93), WEPP-disaggregated breakpoint data for the same rainfall storms are used for EUROSEM simulations. This enables the use of the same data sets for WEPP and EUROSEM simulations.

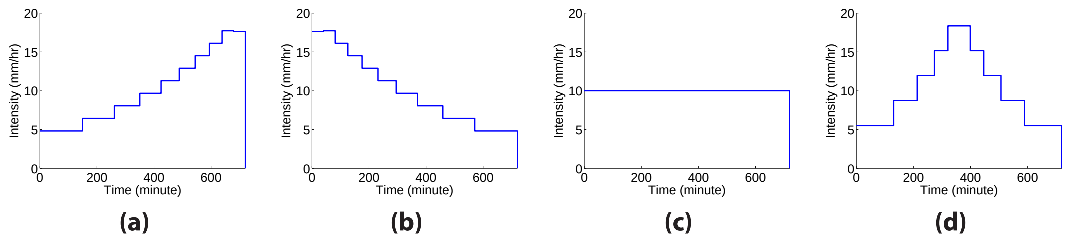


Figure 7.1 Intensity patterns of a stratiform storm for WEPP and EUROSEM simulations. All the inputs have the same total rainfall amount (120 mm) and duration (12 hour). Note the scales of the axes.

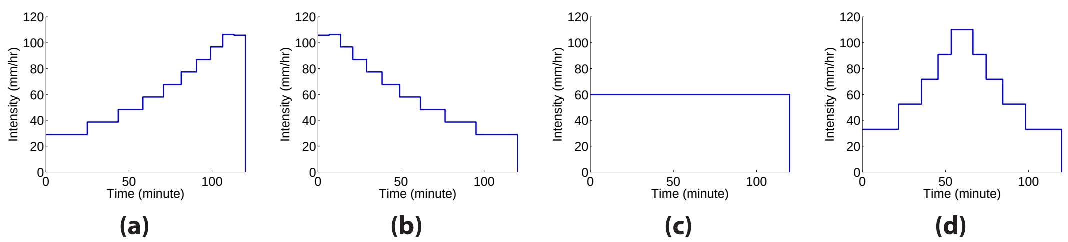


Figure 7.2 Intensity patterns of a convective storm for WEPP and EUROSEM simulations. All the inputs have the same total rainfall amount (120 mm) and duration (2 hour). Note the scales of the axes.

A separate storm with average rainfall intensity of 120 mm/hr (60 mm for 30 min) is designed for RillGrow simulations as shown in Figure 7.3. A separate designed storm is used because of the long computation time required with the version of RillGrow, which is version 2, as discussed previously. The main aim of this chapter is to investigate effects of WSIP on erosion modelling. Thus, in principle, using a separate storm for RillGrow should not have any effects on the investigation result—this is more discussed later in this chapter.

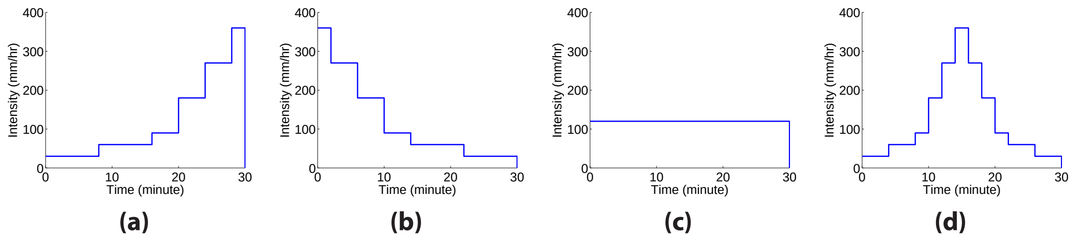


Figure 7.3 Intensity input patterns for RillGrow2 simulations. All the inputs have the same total rainfall amount and duration (i.e. 60 mm rainfall for 30 minutes). Note the scales of the axes.

The effects of WSIP changes on runoff and soil loss estimated by WEPP, EUROSEM and RillGrow are shown in the next section.

7.3 Effects of WSIPs on Runoff and Soil Loss

The summary of WEPP simulation results is shown in Table 7.1. The results are compared against the constant intensity storm in terms of % changes. When 60 mm/hr intensity is used, WEPP estimates the same runoff with all WSIPs. However, for the same intensity, WEPP estimates soil losses with about 5–9% increases with increasing, decreasing and increasing-decreasing WSIPs in comparison to those with the constant WSIP. In contrast, when lower intensity (i.e. 10 mm/hr) is used, WEPP simulates notably different results. While estimated runoff rates are almost the same—less than 2% changes—for all WSIPs, estimated soil loss rates are increased extensively by 5250%, 3750% and 5600%

for increasing, decreasing and increasing-decreasing WSIPs respectively from the soil loss rate for the constant WSIP (Table 7.1). This is because WEPP-estimated soil loss rate with the constant intensity pattern is very small (0.4 t/ha). Runoff and soil loss rates estimated with 60 mm/hr intensity are generally larger than those with 10 mm/hr intensity regardless of WSIPs.

Table 7.1 Summary of WEPP simulation results for varying WSIPs

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.

The summary of EUROSEM simulation results is shown in Table 7.2. For 60 mm/hr and 10 mm/hr intensity, EUROSEM shows the similar responses. When runoff rates estimated by EUROSEM with varying WSIPs with 60 mm/hr and 10 mm/hr intensities are compared to those estimated with the constant WSIP for both intensities, there are not much differences in estimated runoff rates. The magnitude of changes are around 0.3–3% although runoff estimated with 10 mm/hr intensity is smaller than runoff estimated with 60 mm/hr intensity. On the other hand, there are slight decreases in estimated soil loss rates with increasing, decreasing and increasing-decreasing WSIPs in comparison to those estimated with the constant WSIP. Unlike WEPP results, soil loss results show decreases, which are in the similar magnitude, for both intensities: 60 mm/hr and 10 mm/hr. Constant WSIP simulates the largest soil loss rates: 22.6 t/ha and 24.7 t/ha for 60 mm/hr and 10 mm/hr, respectively. The smallest soil loss rates are estimated with increasing WSIP: 19.7 t/ha and 22.1 h/ha for 60 mm/hr and 10 mm/hr, respectively (Table 7.2).

Table 7.2 Summary of EUROSEM simulation results for varying WSIPs

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.

The summary of RillGrow simulation results is shown in Table 7.3. Again, runoff, which is simulated as "Totals lost from edges (litre)", for increasing, decreasing and increasing-decreasing WSIPs does not show much changes from that of the constant WSIP. However, estimated soil loss rates changes when the different WSIPs are used. The largest soil loss rate (90.5 t/ha) is estimated with decreasing WSIP while the constant WSIP produces the smallest soil loss rate (64 t/ha) (Table 7.3). Similar to WEPP results, increasing, decreasing and increasing-decreasing WSIPs result in increases (about 15–40%) in soil loss rates in comparison to the soil loss rates estimated with the constant WSIP.

Table 7.3 Summary of RillGrow simulation results for varying WSIPs

	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

Effect of WSIP on WEPP result In WEPP inputs, t_p represents normalised time-to-peak which is closely related to WSIP. This parameter, t_p, was previously considered rather insensitive (Nearing *et al.*, 1990). Nearing *et al.* (1990) performed sensitivity analysis on WEPP, which was still in the early stage of its 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.

Their findings may not be compared directly with the result presented in this chapter because their analysis was carried out on the developing version of WEPP while this chapter used more recent version of WEPP and the intensity value they used was much higher (100 mm/hr) than the intensities (10 and 60 mm/hr) used in this chapter.

However, as seen in Table 7.1, the timing of peak intensity (or WSIP in this chapter), had visible effects on the result of simulations. It became even more evident when rainfall with low intensity (10 mm/hr) was used with WEPP. For example, when the constant WSIP was used for WEPP simulations, WEPP greatly underestimated soil loss rates by about 50 times less than the average soil loss rate of other WISPs—increasing, decreasing and increasing-decreasing WSIPs (Table 7.1). Thus, it is essential to know about WSIP of the rainfall storm that is used for erosion simulations.

The difference in soil loss with this magnitude (i.e. 50 times) is worryingly large and raises considerable problems, for example, when GCM/RCM rainfall data are directly used for soil erosion modelling. This is because GCM/RCM data are usually used as daily data in which no peak intensity can be identified. In other words, they are used as constant WSIP. Moreover, as discussed previously, disaggregation of such data into sub-daily data is not viable as it increases uncertainty in erosion estimation results.

Effect of WSIP on EUROSEM result EUROSEM, however, resulted in rather different results from WEPP simulation results. Although EUROSEM estimation results were also affected by the change of WSIP, unlike WEPP, EUROSEM simulated less soil loss with increasing, decreasing and increasing-decreasing WSIPs than that with constant WSIP (Table 7.2). In fact, soil loss rates estimated with increasing WSIP was the smallest soil loss rate.

Detailed investigations of the EUROSEM output files showed that slightly less "Gross Interrill Erosion" was estimated with increasing WSIP than with other WSIPs while "Gross Rill Erosion" was estimated at the similar rate for all WSIPs. This was however only seen with 60 mm/hr intensity. When 10 mm/hr intensity was used, EUROSEM estimated slightly less "Gross Rill Erosion" with increasing WSIP than with other WSIPs. "Gross Interrill Erosion" was almost negligible for all four WSIPs when 10 mm/hr intensity was used. This confirms again that EUROSEM dynamically changes its modelling mode depending on the surface condition so that the proportion of rill and interrill erosion for the total erosion changes. Also, This shows that the responses of EUROSEM—in terms of total erosion rates—to the change of WSIP are the same regardless of the average rainfall intensity: the smallest soil loss rate is estimated with increasing WSIP.

In addition, in comparison to the previous chapter, Chapter 6, EUROSEM estimated increased soil loss with lower average intensity (10 mm/hr) than with higher average intensity (60 mm/hr). This increase of soil loss rates was even accompanied with decreased runoff rates. These EUROSEM simulation results are unrealistic and may imply that EUROSEM is subject to some model improvements in this regard.

Effect of WSIP on RillGrow result RillGrow simulated, for constant WSIP, about 78% soil loss from the average soil loss of storms with other WSIPs. RillGrow also estimated the largest soil loss with decreasing WSIP in comparison to those estimated with other storm patterns. Runoff simulated by RillGrow with varying WSIPs was, on the other hand, not affected because of no infiltration was considered as discussed in the previous chapter.

The result from RillGrow simulations with constant and decreasing WSIPs was consistent with the result from the study by Parsons and Stone (2006). Parsons and Stone (2006) conducted a series of lab experiments to investigate the effects of five different intensity patterns (i.e. constant, increasing, decreasing, increasing then decreasing and decreasing then increasing intensity) on soil erosion (Table 7.4). They found that the constant-intensity storm generated the least amount of soil loss which was about 75% of the average soil loss for the variable-intensity storms. Also, the largest soil loss amount was occurred when decreasing-intensity pattern was used.

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.

By comparing the soil loss results estimated with WEPP, EUROSEM and RillGrow with the result from Parsons and Stone (2006), it was found that RillGrow showed the similar results for constant and decreasing WSIPs with which the smallest and largest soil loss rates were simulated, respectively (Table 7.5). Also, WEPP showed the consistent results with Parsons and Stone (2006) for constant and increasing WSIPs with which the smallest and the second largest soil loss rates were estimated, respectively. However, some of other simulation results were not consistent with the result from Parsons and Stone (2006). For example, EUROSEM simulation results were completely inconsistent as the largest soil loss was estimated by EUROSEM with constant WSIP and the smallest soil loss was estimated with increasing WSIP.

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

Despite WEPP and RillGrow simulation results were partially consistent with the results from Parsons and Stone (2006), they still showed inconsistent responses to the change of WSIP for, for example, WEPP with increasing-decreasing and decreasing WSIPs and RillGrow with increasing-decreasing and increasing WSIPs. This means that erosion models still simulate different responses to the change of WSIP compared to the measured responses. This difference need to be improved by more lab or field experiments that can be compared to the model results. As fas as this research is aware, there are no other lab or field experiments that can be compared against model responses to the change of WSIPs except the study by Parsons and Stone (2006). Thus, there is an urgent need for such research.

7.5 Conclusion

It was shown in this chapter that WSIP (or t_p for WEPP) is a important factor for erosion estimations. Without knowing details of WSIPs, erosion models could easily estimate soil erosion with great variabilities as shown in WEPP results. Effects of WSIPs on runoff estimations were however small implying WSIP affects soil loss rate more.

The change of WSIP with high intensity have less impacts on soil loss estimations than the change of WSIP with low intensity. Despite varying responses of the erosion models to the change of WSIP, constant WSIP produced the least soil loss when used with WEPP and RillGrow.

There are urgent needs for more lab or field experiments that can be compared with the model results in order to improve model predictabilities.

7.6 Summary of Model Simulation Result: Effect of WSIV, WSG and WSIP

In Part II, *Rainfall Intensity and Erosion: Model Descriptions and Responses*, various factors, which are related to rainfall intensity of a storm, have been investigated in terms of their effects on soil erosion. These factors (i.e. temporal resolution of rainfall data, WSG and WSIP) are closely related to the simulation result that are estimated by WEPP, EUROSEM and RillGrow.

During these investigations, we have found:

- Chapter 5:
  - Temporal resolutions of rainfall data affect Within-Storm Intensity Variations (WSIVs)
  - Temporal resolutions of rainfall data are closely related to the estimated results of runoff and soil loss
  - In terms of soil loss, WEPP is more sensitive to the change of temporal data resolutions than EUROSEM
  - Erosion estimations with CLIGEN data are more affected by the change of temporal resolutions than those with breakpoint data

  - Breakpoint data are preferred to CLIGEN data as far as investigations on effects of rainfall intensity on erosion are concerned
  - For the subsequent analyses of this research, 15-min breakpoint rainfall data are chosen

- Chapter 6:
  - Within-Storm Gaps (WSGs) affected estimated runoff and soil loss by WEPP and EUROSEM.
  - WSG have almost no effect on runoff and soil loss estimated by RillGrow.
  - Although it was not evident to conclude whether WSGs have positive or negative effects on runoff and soil loss estimations, the removal of WSGs from original data affected model simulation results.
  - Thus, removing WSGs from the original rainfall data is not recommended
  - Analyses of outputs from WEPP simulations revealed new problem that WEPP modifies original rainfall intensity and simulates unrealistic results.
  - When breakpoint data with temporal resolutions shorter than 60-min temporal resolution is used for WEPP simulations, WEPP constructs "WEPP-modified" rainfall data which have different rainfall intensity information from original rainfall intensity.

- Chapter 7:
  - Within-Storm Intensity Pattern (WSIP) affects soil loss rates estimated by WEPP, EUROSEM and RillGrow.
  - Effects of the change of WSIP on runoff rates estimated by the same models are relatively small compared to those on estimated soil loss rates.

- The change of WSIP with high intensity have less impacts on soil erosion estimations than the change of WSIP with low intensity.
- The smallest soil loss rate was estimated with constant WSIP when WEPP and RillGrow were used
- Comparisons with the result from the only laboratory experiment by Parsons and Stone (2006) showed that WEPP and RillGrow simulation results are almost consistent to the observational result: The smallest soil loss rate was estimated by WEPP and RillGrow with constant WSIP.

The effect of intensity-related factors on runoff and soil loss found in Part II are summarised in Table 7.6.

Unarguably, there are more studies on effects of rainfall amount on runoff and soil loss rates than studies on effects of rainfall intensity. This may be because our interests are given more to the relationship between soil erosion and rainfall amount than relationship between soil erosion and rainfall intensity, or maybe because details of rainfall intensity are simply difficult to record and obtain. In any case, this research showed that the changes of rainfall intensity play an important role in erosion modelling, and recognised the need for more researches that looks into the effect of rainfall intensity changes on runoff and soil loss.

Currently, only observational results available for the comparison analyses were from the laboratory experiment carried out by Parsons and Stone (2006). Their research only concerns about the effect of WSIP changes. However, as shown in this research, more experiment studies on other intensity-related factors considered in this thesis such as WSG and WSIV are required. It will then enable us to understand more on the interaction between rainfall intensity and soil erosion. Needless to say, without being able to predict (or simulate) present soil erosion, it will be very hard to accept any

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

Intensity Pattern		Erosion Model: WEPP[1]	Erosion Model: EUROSEM[1]	Erosion Model: RillGrow	Measurement: 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

prediction done for the future condition because of possible increases of uncertainty for the future.

The result of this research is however limited by the lack of observational data. All of the results showed here are model-estimated values and only a small number of modelling results was compared to the observed (or lab-experimented) data. This limitation can only be solved by comparing the estimated result against observational results from more laboratory or field experiments.

PART III

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

Chapter 8

ESTIMATION OF SOIL EROSION: IMPLICATIONS FOR FUTURE RAINFALL INTENSITY

8.1 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 of current techniques for 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 do not, 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, all is not lost. It may still be possible to draw some inferences regarding 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 3; *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 data for future rainfall, 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).

8.2 Possible Approaches to Simulating Future Rainfall 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 WSG is vital in order to carry out future erosion predictions. To achieve the aim of this research, an alternative approach has to be sought to obtain future rainfall data with a appropriate data resolution and 'changed' rainfall intensity. The process of finding alternative approach is discussed in this section.

8.2.1 Approach 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. One reason is that it is not possible to change the number of raindays using this approach. It does not make a full use of the findings from the previous analyses. This is an indirect approach.

8.2.2 Approach 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:

$$D = M\Delta t\delta \tag{8.1}$$

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:

$$\text{MX.5P} = \frac{1}{K}\sum maxI_{30} \tag{8.2}$$

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:

$$\frac{0.8 + 0.9 + 0.3 + 2.8 + 1.5}{5} = 1.26 \text{ (in/hr)}. \tag{8.3}$$

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 8.1). 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 8.1 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 only the sensitivity-type comparison.

It is very unlikely all the months 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 8.2). The dry season consists of March, April, May, June, July and August (Table 8.3).

Table 8.2 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 8.3 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

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 *et al.* (1995) has recognised the close statistical relationship between MX.5P and soil erosion rate. Thus, it is unsurprising that this parameter is explicitly included in the 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 rainfall amount will very probably also 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.

8.2.3 Approach 3: Using GCM/RCM Data

This third approach 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 approach 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 temporal resolution—that is, 30-min time step—for building CLIGEN input files. This will permit a "better"—in the sense of being more realistic—judgement of impacts of rainfall intensity changes on future soil erosion.

A major caveat is that the high resolution GCM data are still not readily available. A separate model configuration is required to generate this kind of data, and the set-up process 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.

8.2.4 Conclusion: Selected Approach

Approach 2 (Section 8.2.2) is selected. The schematic procedure of this approach is shown in Figure 8.1. It was assumed that future WSIV, WSG 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 8.1). 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.

8.3 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 duration, D can be described as:

$$I = i_p \times \frac{R}{D} \tag{8.4}$$

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

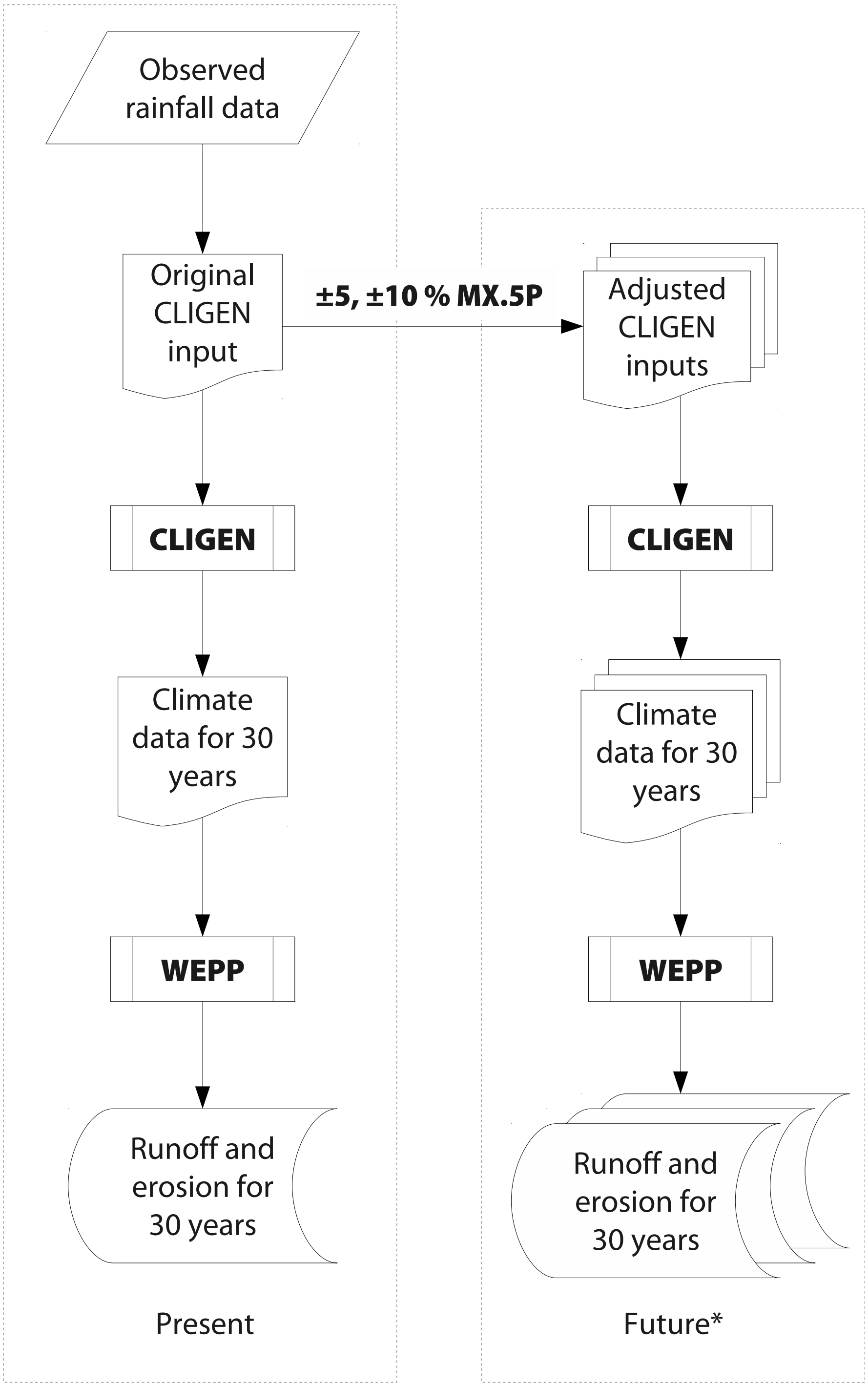


Figure 8.1 Schematic flowchart of the approach which is used for investigation of implications of rainfall intensity changes for future soil erosion. Soil erosion simulated in the left-side box marked with 'Present' represents the present erosion rate under current rainfall intensity. Soil erosion simulated in the right-side box marked with 'Future*' represents assumed future erosion rates under the different rainfall intensities.

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 8.4). All other factors, such as rainfall frequency and seasonal intensity variation, are unchanged.

Table 8.4 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 C.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.

8.3.1 Runoff and Soil Loss

The mean annual soil loss estimated by WEPP increases or decreases as peak intensity increases or decreases (Figure 8.2). 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 8.2.

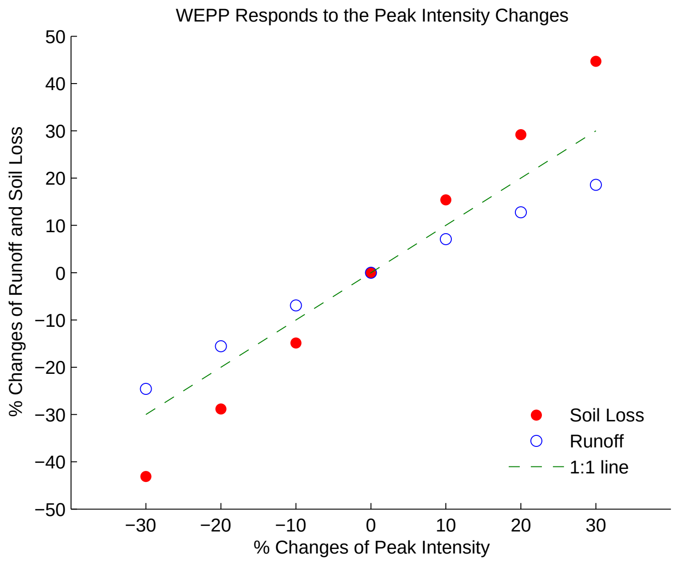


Figure 8.2 WEPP responses to the peak rainfall intensity changes

8.3.2 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 unrealistic. This is because of 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 page 124).

8.4 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, 2001*b*).

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 resolutions of rainfall data (WSIV)
- within-storm intensity pattern (WSIP)
- continuity of rainfall duration (WSG)

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.

8.4.1 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 8.3).

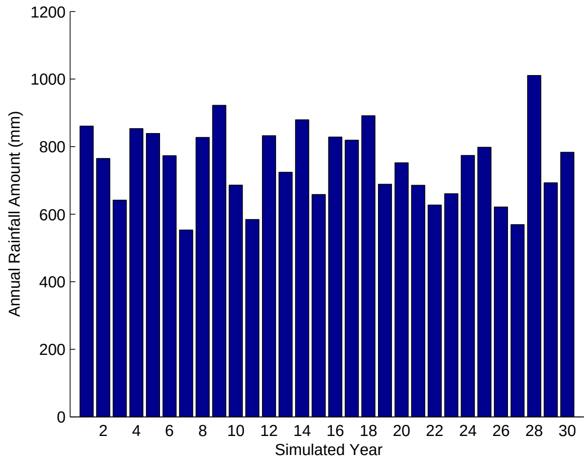


Figure 8.3 Simulated annual rainfall amount using CLIGEN

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 8.4). For the changes in dry season, the magnitude of the change was more gradual than that of the wet season (Figure 8.4). Every 1% change in the peak intensity of dry season caused a −0.45% change in annual rainfall duration 8.4.

The changes in average monthly maxima of daily peak intensity for wet and dry season affected CLIGEN-simulated daily peak rainfall intensities (Figure 8.5). 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).

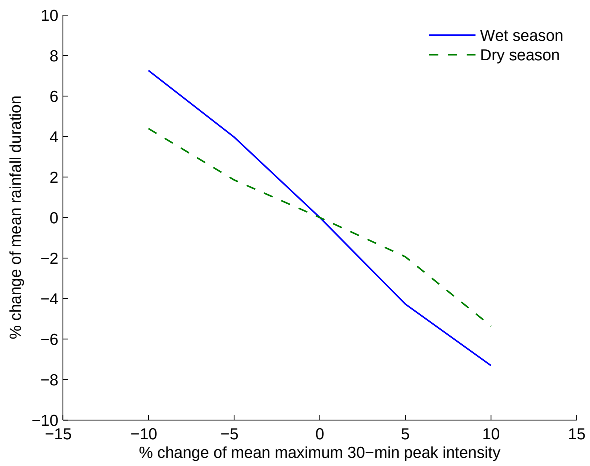


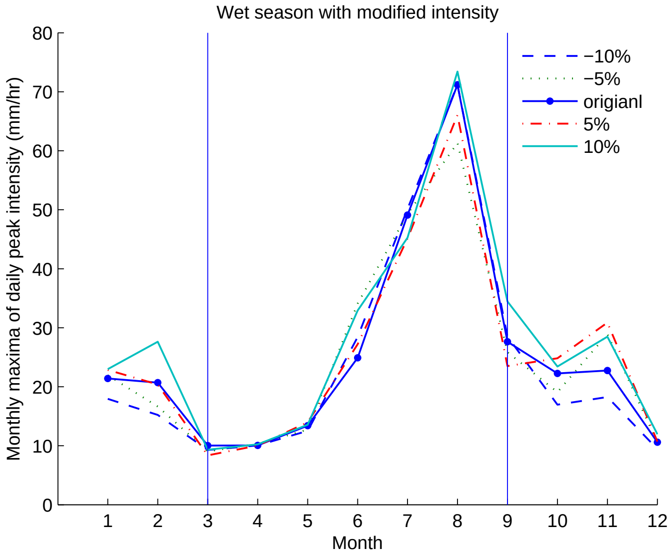
Figure 8.4 Simulated annual rainfall duration changes by changing mean maximum 30-min peak intensity for wet and dry seasons.

8.4.2 Estimated Changes of Future Soil Erosion

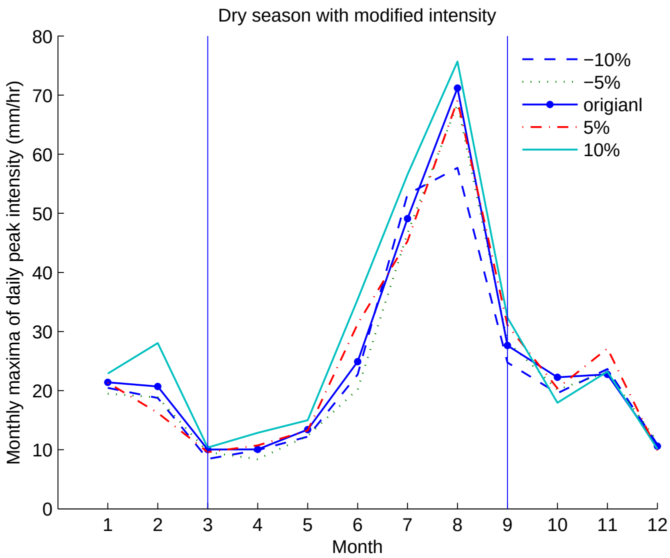
For the wet season, increases or decreases in mean maximum 30-min peak intensity generally yield increases or decreases in runoff. Every 1% change in the mean maximum 30-min peak intensity for the wet months (SONDJF) resulted in about a 0.72% change in the mean annual runoff (Figure 8.6). For the dry season, 5% change in mean maximum 30-min peak intensity yield the greatest changes in runoff (Figure 8.6) 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 8.7). 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 8.7).

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

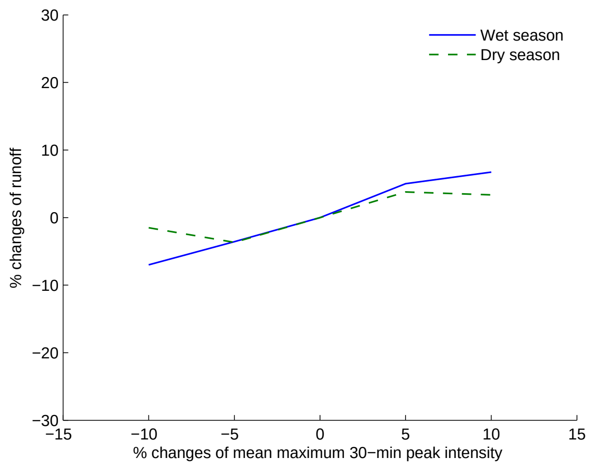


Figure 8.6 Runoff changes in response to the changes of mean maximum 30-min peak intensity for wet and dry seasons.

significant effect on soil loss rates except a 5% increase in the intensity (Figure 8.7). 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 8.7). 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).

8.4.3 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

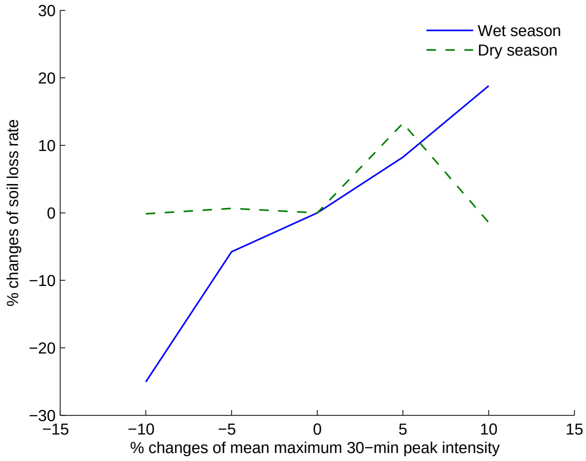
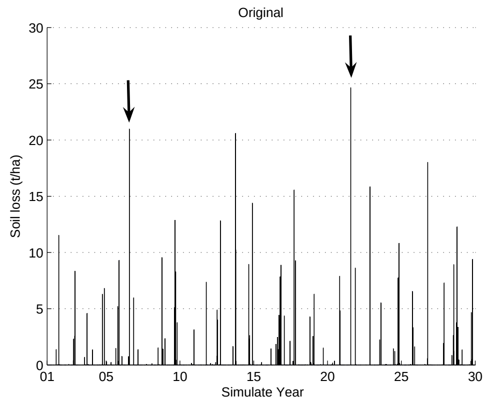


Figure 8.7 Soil loss rate changes in response to the changes of mean maximum 30-min peak intensity for wet and dry seasons.

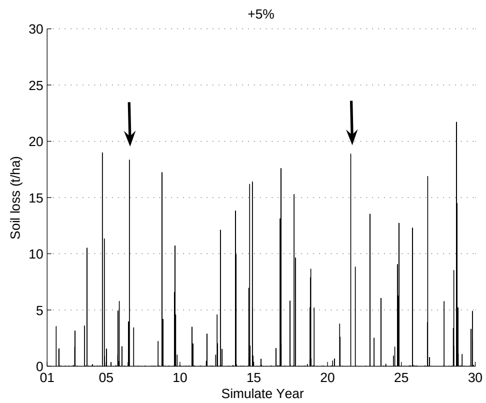
the dry season.

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 8.8). 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 3.6).

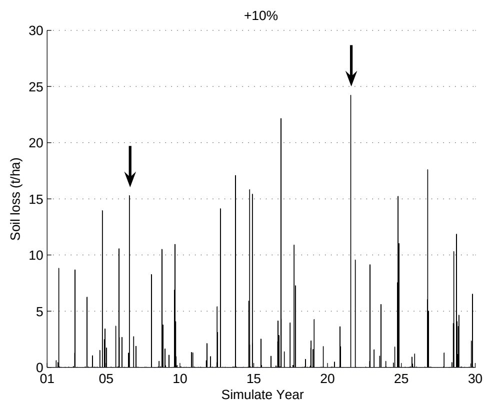
The intensity increase in dry months is not significant to cause a change in erosion rate as either they do not have sufficient rainfall amounts to initiate erosion or surface conditions are not susceptible for erosion because of sufficient crop covers. The rainfall intensity becomes more important where 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 8.8 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 8.5a). A similar effect is also observed when monthly mean maximum 30-min peak intensity in the dry months are changed (Figure 8.5b). 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.

8.5 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 9

CONCLUSION

The main objective of this research has been to investigate the implications of change in future rainfall intensity for future soil erosion by water, by analysing the response of erosion models to arbitrary rainfall intensity changes, and implicitly, the process understanding on which the the erosion models are based. Therefore, this research can be regarded as a step towards the ultimate goal of predicting future soil erosion rates caused by future rainfall intensity changes.

The current research has been carried out in two parts: *Rainfall Intensity and Erosion: Model Descriptions and Responses* and *Implications for Model-based Studies of Future Climate Change and Soil Erosion*.

In Part I, *Rainfall Intensity and Erosion: Model Descriptions and Responses*, WEPP, EUROSEM and RillGrow were used to investigate the:

- information regarding rainfall intensity which is needed to simulate soil erosion,
- responses of selected erosion models to various changes in rainfall intensity,

- representation of the effects of rainfall intensity on erosion within each erosion model,
- applicability of these erosion models for future research.

Then, in Part II, *Implications for Model-based Studies of Future Climate Change and Soil Erosion*, the best approaches for building scenarios of future rainfall intensity changes were discussed based on the findings from the previous part. This was then followed by the erosion simulations by WEPP with this future intensity scenario. Part II thus aimed to:

- suggest the best currently-available way of investigating impacts of rainfall intensity changes on future erosion and
- test this method using scenarios of future change in rainfall intensity.

To achieve these aims of this research, following research questions was 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 a future climate, and that this future climate has different rainfall intensity from the present, what information (both regarding climate, and regarding erosion processes) do we need to make predictions of soil erosion rates under that future climate?

Question 3. From the above, are we in a position to predict soil erosion under the future climate? If not, what more is necessary?

In this chapter, the main findings of each part of this thesis are summarised with respect to the above research questions. The chapter consists of three sections. The first section outlines the findings from Part I. In the second section, these findings from Part I are linked with the research questions and answers are discussed. Finally, the third section outlines perspectives for future research on effects of rainfall intensity changes on soil erosion.

9.1 Summary of Model Responses to Rainfall Intensity

9.1.1 Effect of Temporal Resolution of Storm Data

There is a close relationship between temporal resolution of rainfall data and soil erosion estimations. When temporal resolutions of rainfall data changes (increase or decrease), rainfall intensities also changes (decrease or increase). Temporal resolution of rainfall data thus is closely related to WSIVs as well. Model simulation results can be up to about 30 times different from the "original results" if rainfall data with low temporal resolution are used. This magnitude is so great that it might mean from almost no erosion to disastrous events.

In terms of soil loss, WEPP is more sensitive to the change of temporal data resolutions than EUROSEM. Breakpoint data are preferred to CLIGEN data for erosion modelling because they are less affected by the change of temporal resolutions than CLIGEN. Where it is available, 15-min breakpoint rainfall data are recommended for erosion simulations.

9.1.2 Effect of Within-Storm Gap

It is not evident if WSG has positive or negative effects on soil erosion estimations. However, removing WSG from original rainfall data affects the model simulation results by WEPP and EUROSEM. Therefore, it is not recommended to remove WSG from the original rainfall data. It is a best practice to use rainfall data which have all necessary information for erosion modelling.

When breakpoint data with a temporal resolution shorter than 60-min temporal resolution is used, WEPP modifies original rainfall intensity information and simulates erroneous erosion rates. This is a major problem for current research and for our ability to predict erosion. This is also a major model fault for WEPP. Even if 15-min breakpoint rainfall data, as suggested previously, are available for WEPP simulations, WEPP is not capable of utilising original rainfall intensity information and simulates unrealistic soil erosion. Until this problem is resolved, interpreting WEPP outputs which are generated with breakpoint data requires additional cautions. Therefore, an urgent improvement work is needed for WEPP.

9.1.3 Effect of Within-Storm Intensity Pattern

WSIP also has effects on soil loss estimations. Effects of WSIP on runoff estimations are however small implying that WSIP affects estimations of soil loss rates more. WSIP of a rainfall storm with high intensity has less impacts on soil loss estimations than WSIP of a rainfall storm with low intensity. Despite varying responses of WEPP, EUROSEM and RillGrow to WSIP, constant WSIP produced the least soil loss rates for WEPP and RillGrow. There are urgent needs for more laboratory or field experiments that can be compared with the model results in order to improve model predictabilities.

9.2 Answers to Research Questions

9.2.1 What role does rainfall intensity play in the process descriptions which comprise erosion models?

There is a difference between the theoretical treatment of rainfall intensity in erosion models, and the practical handling of it. For example, increased rainfall intensity is not always accompanied by estimations of increased runoff and soil loss as shown in Part I of this thesis. Effects of rainfall intensity changes on erosion modelling largely depend on the process descriptions on which erosion models are based. However, rainfall intensity undoubtedly plays an important role in estimating runoff and soil loss rates.

As shown previously, Within-Storm Intensity Variation (WSIV) are related to temporal resolution of rainfall data, Within-Storm Gap (WSG) and Within-Storm Intensity Pattern (WSIP). Temporal resolution of rainfall data affects the results of erosion simulations. When temporal resolution of rainfall data increases, the amount of estimated soil loss also increases. Thus, simulation studies which use rainfall data with different temporal resolutions will give different amounts of estimated soil loss.

Secondly, WSG also have a marked effect on erosion estimations. Discontinuous storms (i.e. with WSGs) 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 WSGs removed), since the longer duration of the discontinuous storm reduces the average intensity for the storm, compared with the continuous storm. However, an unexpected result was found from WEPP simulations that more soil loss was estimated with discontinuous rainfall than with continuous rainfall. Original rainfall data is internally reconstructed to "WEPP-modified" data, and this modified data is used in the simulations.

Lastly, WSIP affects the results of erosion simulations. Rainfall events with a constant WSIP produced notably small erosion rates compared to those with other WSIPs. WSIP affects estimations of soil loss rates more than estimations of runoff.

Limitation of model simulation results No comparisons of estimated runoff and soil loss rates against measured runoff and soil loss rates were possible because of the lack of observed erosion data for the individual events considered. However, the changes in runoff and erosion rates from laboratory experiments with similar storm intensity patterns show similar runoff and erosional responses to the change of WSIP. Better comparisons between modelling results and observed data can only be made when there is more observational data.

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.

9.2.2 What information do we need to make predictions of soil erosion rates under future climate?

To predict soil erosion rates under future climate, the following is required:

1. Long-term rainfall data, preferably breakpoint data, with adequately high temporal resolution—high enough to capture details of Within-Storm Intensity Variations (WSIVs)
2. Quantity (%) of Within-Storm Gaps (WSGs)
3. Information about Within-Storm Intensity Patterns (WSIPs)

4. Erosion model that can make proper use of rainfall intensity information such as WSIV, WSG and WSIP

5. Erosion model that can simulate long-term soil erosion continuously—a continuous simulation model.

9.2.3 Are we in a position to predict soil erosion under the future climate? If not, what more is necessary?

Based on the findings from this research, the simplest answer to this question would be "No, we are not." However, this does not mean to say that it is impossible forever. We just are not *YET* in a position to predict soil erosion under the future climate with reasonably acceptable uncertainties.

First reason is that there are some major disagreements found between rainfall data availability and the data requirement suggested by this research. For example, in order to determine effects of rainfall intensity changes on soil erosion, we need high resolution rainfall data such as tipping-bucket recorded data. However, the availability of such data is relatively low because of, for example, data storage issues as discussed previously. The resolution of rainfall data need to be high enough to hold adequate rainfall intensity information such as WSIV, WSG, WSIP for erosion models.

Secondly, erosion models still have inadequate process descriptions for rainfall intensity. For example, WEPP modifies the accumulated time of original breakpoint data and changes rainfall intensity of original storm before it uses them for erosion simulations. Also, WEPP and EUROSEM have the limits on the total number of breakpoint they can process.

Despite these problems, 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 important 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. Therefore, this research assists in improving the performance of erosion models with respect to changes of rainfall intensity by highlighting where current problem exists.

In conclusion, greater knowledge found here will, once future changes in rainfall intensity become better known and appropriate rainfall data become available, improve our ability to estimate future rates of erosion.

9.3 Perspectives for Future Research

The greatest 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.

Therefore, a number of future research topics can be suggested.

1. Laboratory or field experiments on effects of Within-Storm Gaps (WSGs)
2. More laboratory experiments on effects of Within-Storm Intensity Patterns (WSIPs) with more complex intensity patterns
3. Further investigation of Within-Storm Intensity Variations (WSIVs): determination and quantification of WSIV
4. Developments/improvements of erosion models that can make appropriate use of the rainfall information (WSIPs, WSIVs and WSGs)
5. Investigations and predictions of the trends of WSIPs, WSIVs and WSGs

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Appendices

Appendix A

OBSERVED RAINFALL CHARACTERISTICS OF THE STUDY AREA

A.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 resolution 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 resolution 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 resolution, that is a larger resolution 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 resolution. This resolution 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 remembered 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.

A.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 A.1). Daily rainfall intensity is obtained by dividing the monthly rainfall amount by the number of raindays.

Table A.1 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 A.2). 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.

Table A.2 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

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.

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.

A.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 A.1).

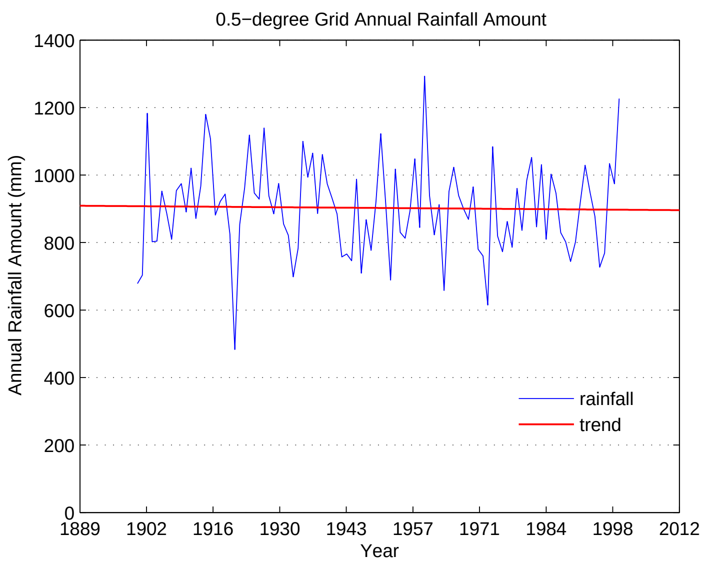
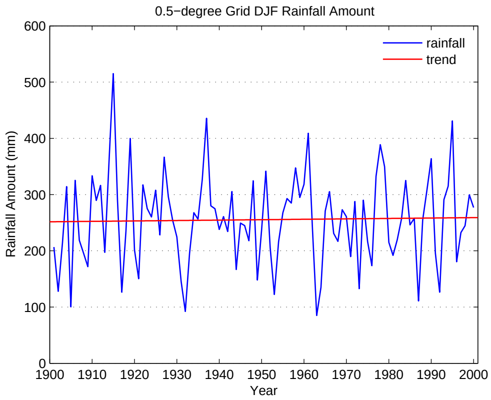


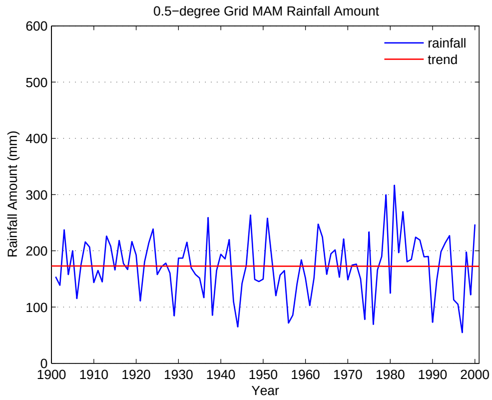
Figure A.1 Annual rainfall amount trend of monthly grid data

There is no statistically significant trend in seasonal rainfall amounts (Figure A.2).

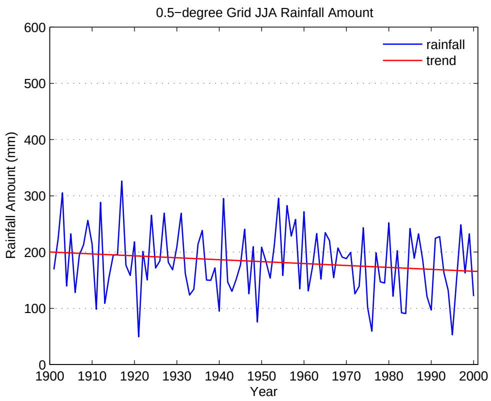
Monthly rainfall amount pattern shows more rainfall in autumn and winter months with a peak in November, and less rainfall in spring and summer months (Figure A.3). Monthly analysis of the grid data shows more detailed monthly trend in rainfall amount.



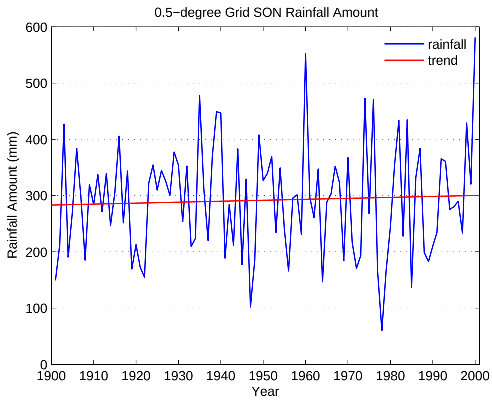
(a) DJF



(b) MAM



(c) JJA



(d) SON

Figure A.2 Seasonal rainfall amount trend of monthly 0.5° grid data

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.

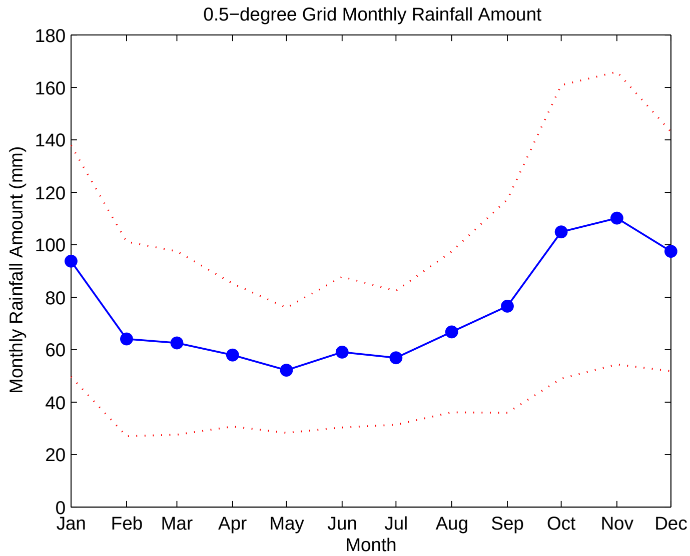


Figure A.3 Average monthly rainfall patterns of monthly grid data. Dotted lines indicate standard deviation with 95% confidence level.

Rainfall amounts in July have a decreasing trend throughout the whole data period (1901–2000) (Figure A.4).

A.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.

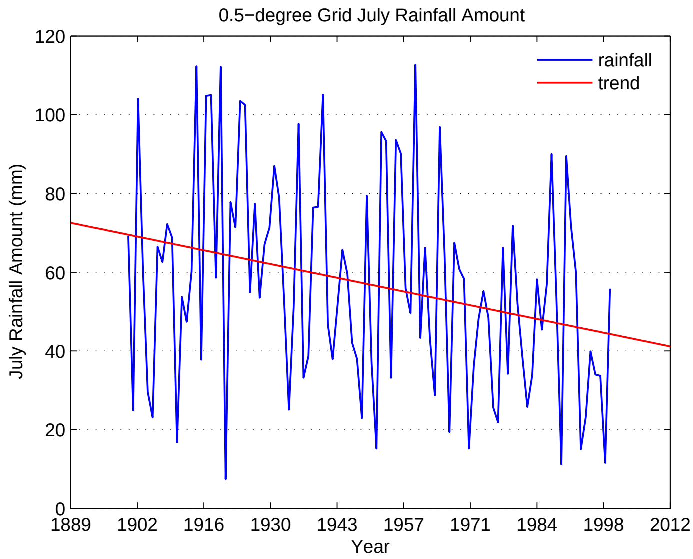


Figure A.4 July rainfall amount trend over 1901-2000

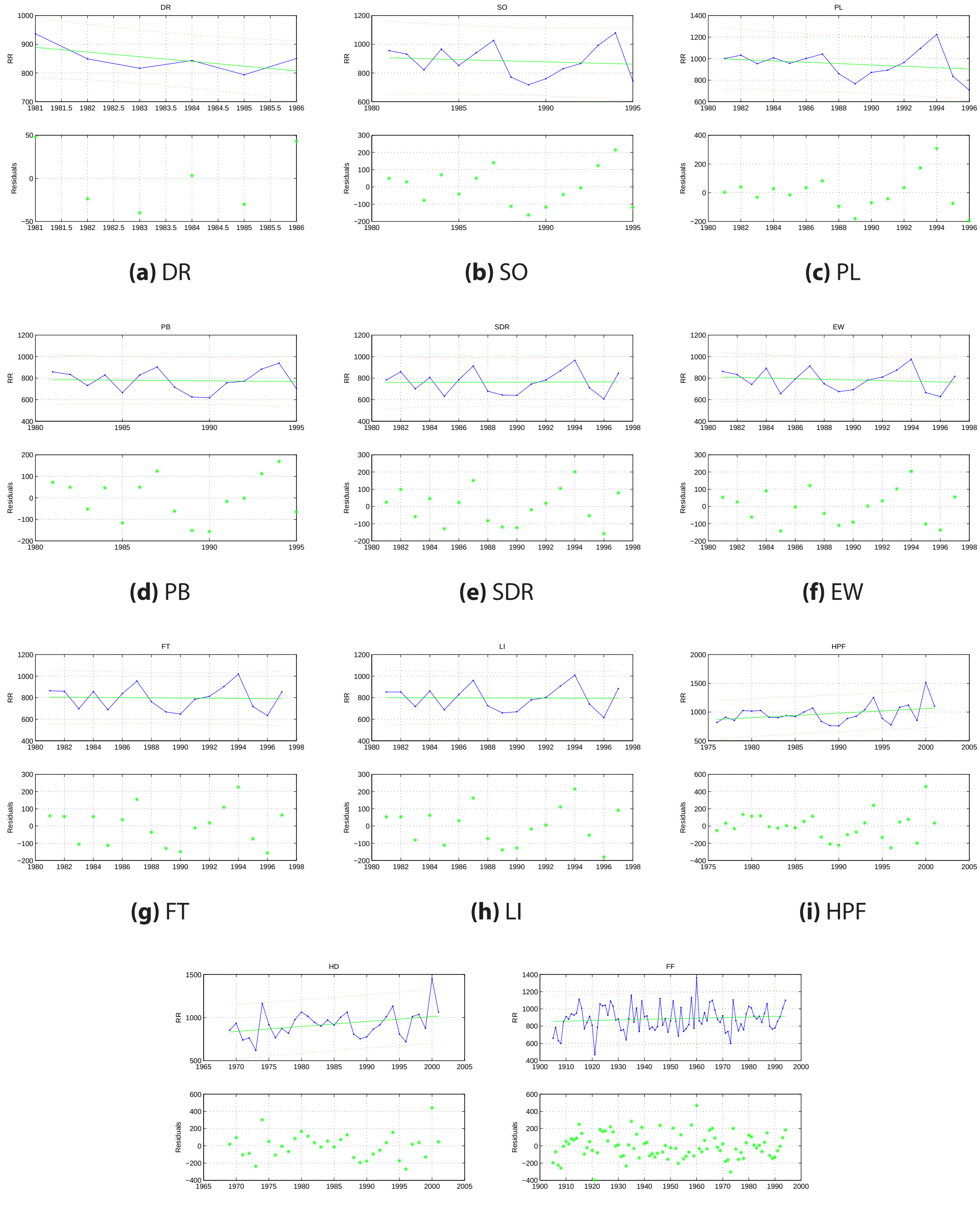
Number of Wet Days (RR1) The number of wet days per year decreased at PL and FF stations (M-K, $p < 0.05$) (Figure A.6). Although not all the stations showed statistically significant annual trends, the ones with significant annual trend in the number of wet days show downward trends in the number of 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 showed upward annual trends in SDII throughout the data periods (Figure A.7). 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 A.8). 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 A.9k).

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 A.10).



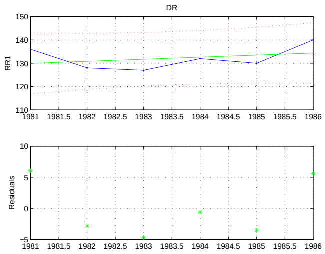
(a) DR **(b)** SO **(c)** PL

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

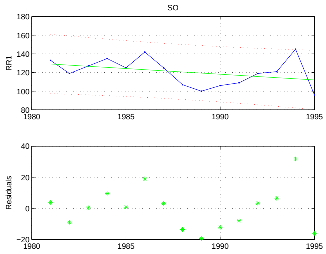
(g) FT **(h)** LI **(i)** HPF

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

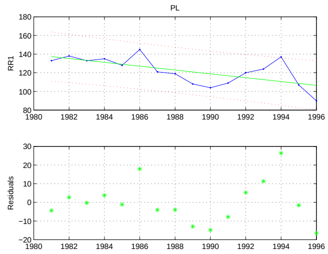
Figure A.5 Trends of annual rainfall amount (RR) at daily data stations



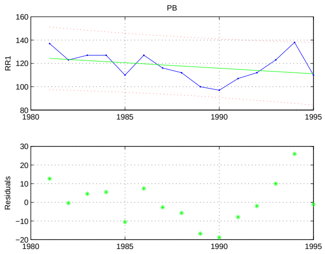
(a) DR



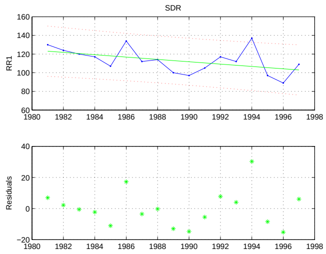
(b) SO



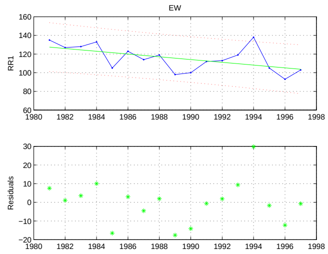
(c) PL



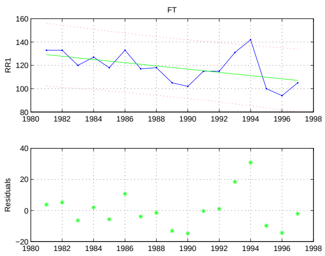
(d) PB



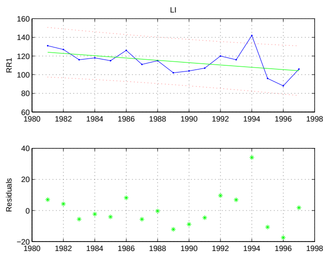
(e) SDR



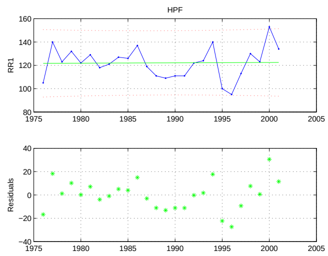
(f) EW



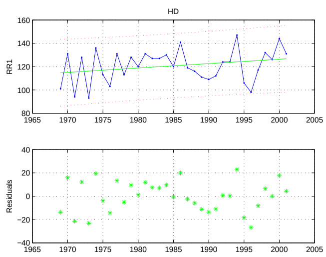
(g) FT



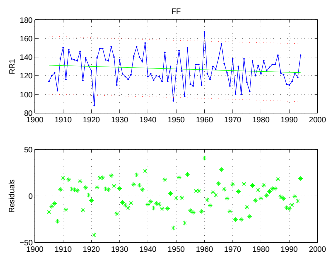
(h) LI



(i) HPF



(j) HD



(k) FF

Figure A.6 Trends of number of wetdays (RR1) at daily data stations

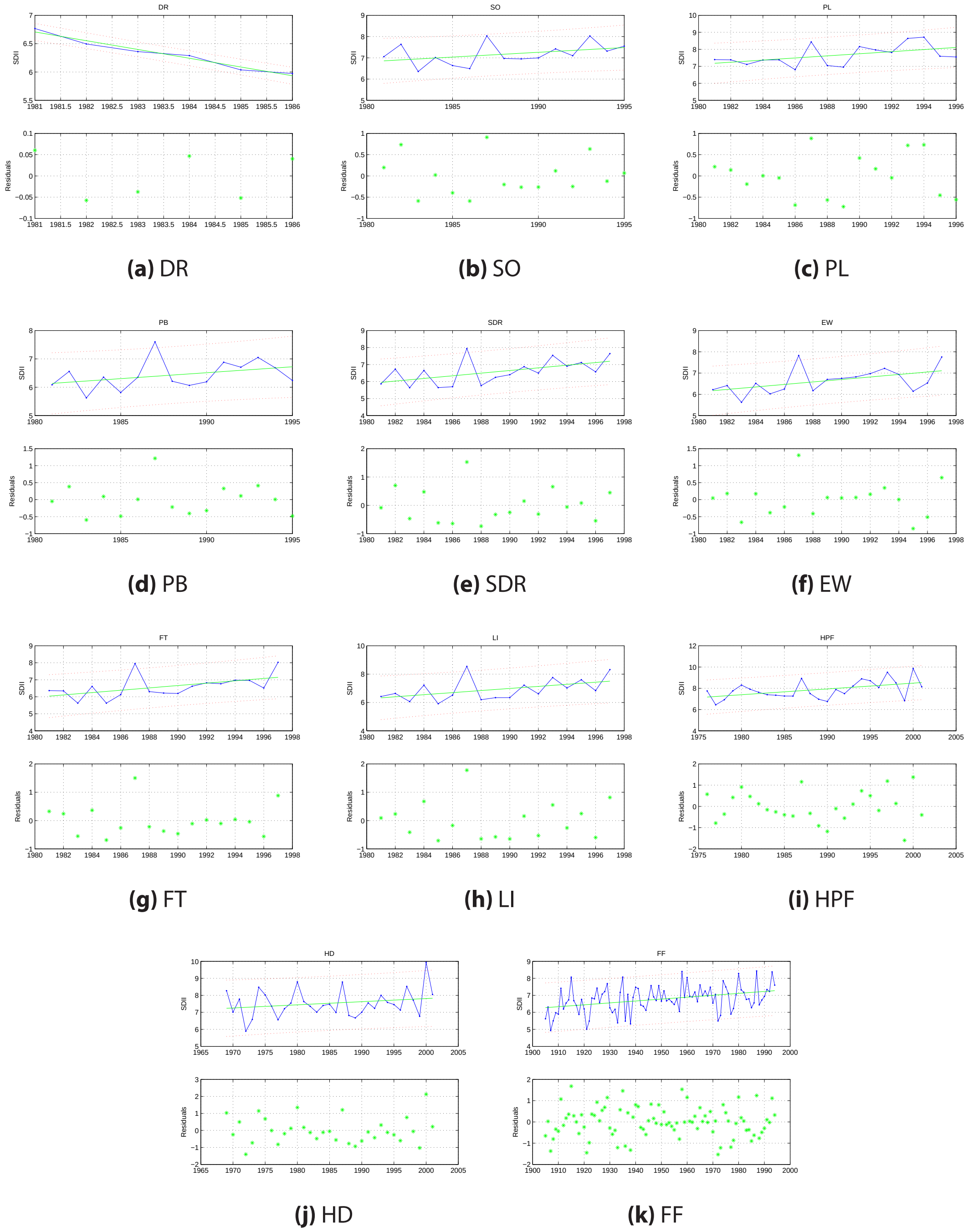
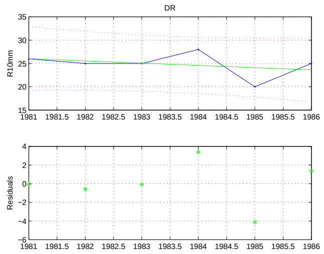
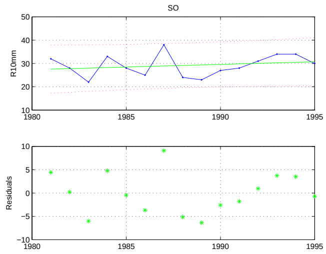


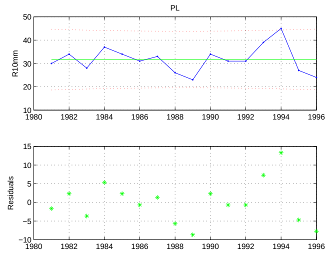
Figure A.7 Trend of annual simple daily intensity index (SDII) at daily data stations



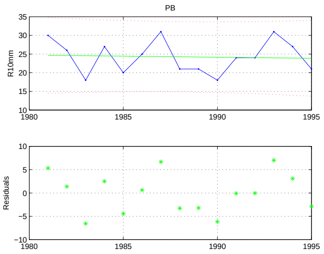
(a) DR



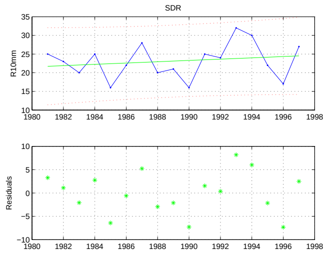
(b) SO



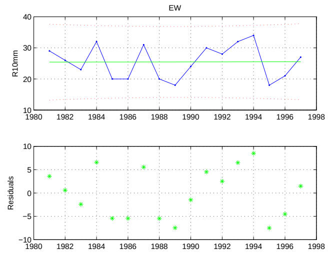
(c) PL



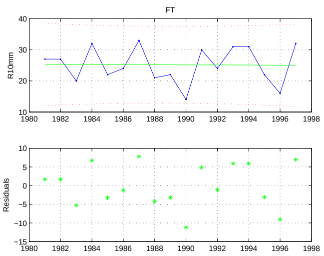
(d) PB



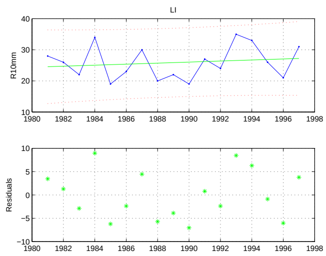
(e) SDR



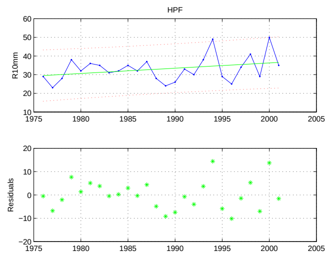
(f) EW



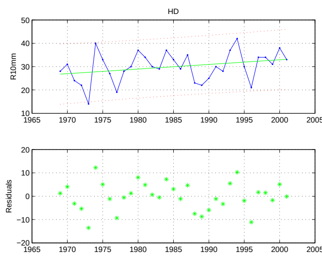
(g) FT



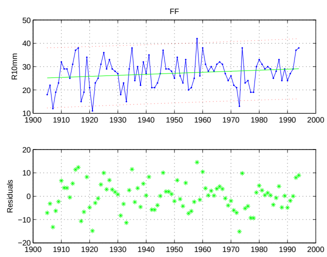
(h) LI



(i) HPF

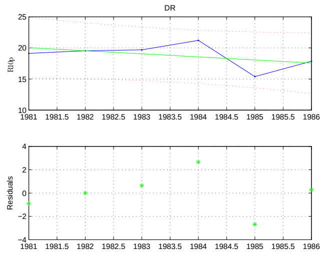


(j) HD

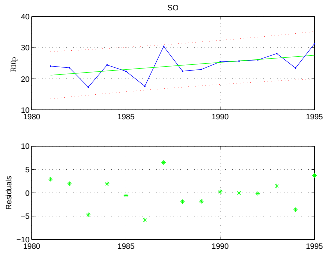


(k) FF

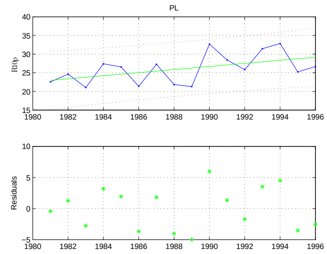
Figure A.8 Annual number of wet days with rainfall amount ≥ 10 mm at daily data stations



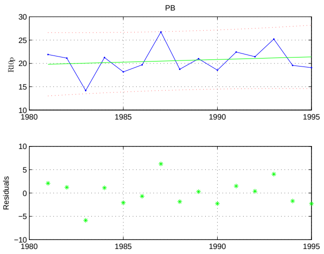
(a) DR



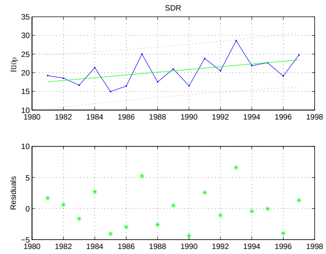
(b) SO



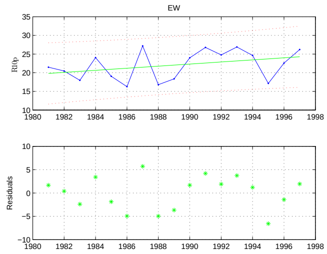
(c) PL



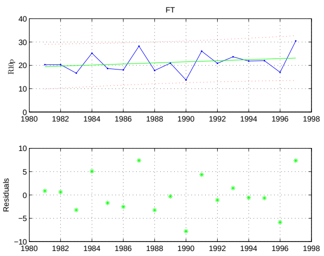
(d) PB



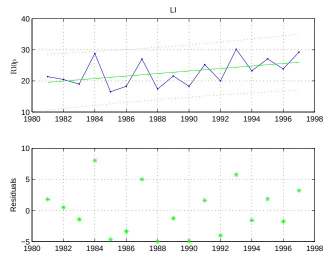
(e) SDR



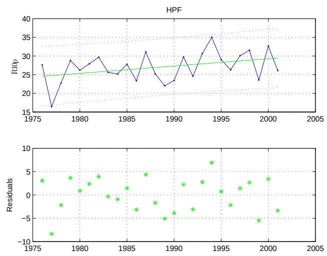
(f) EW



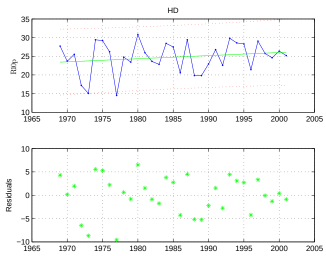
(g) FT



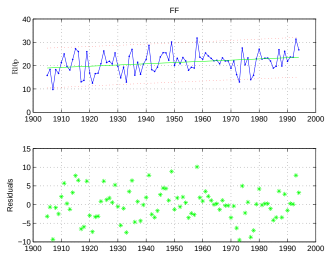
(h) LI



(i) HPF

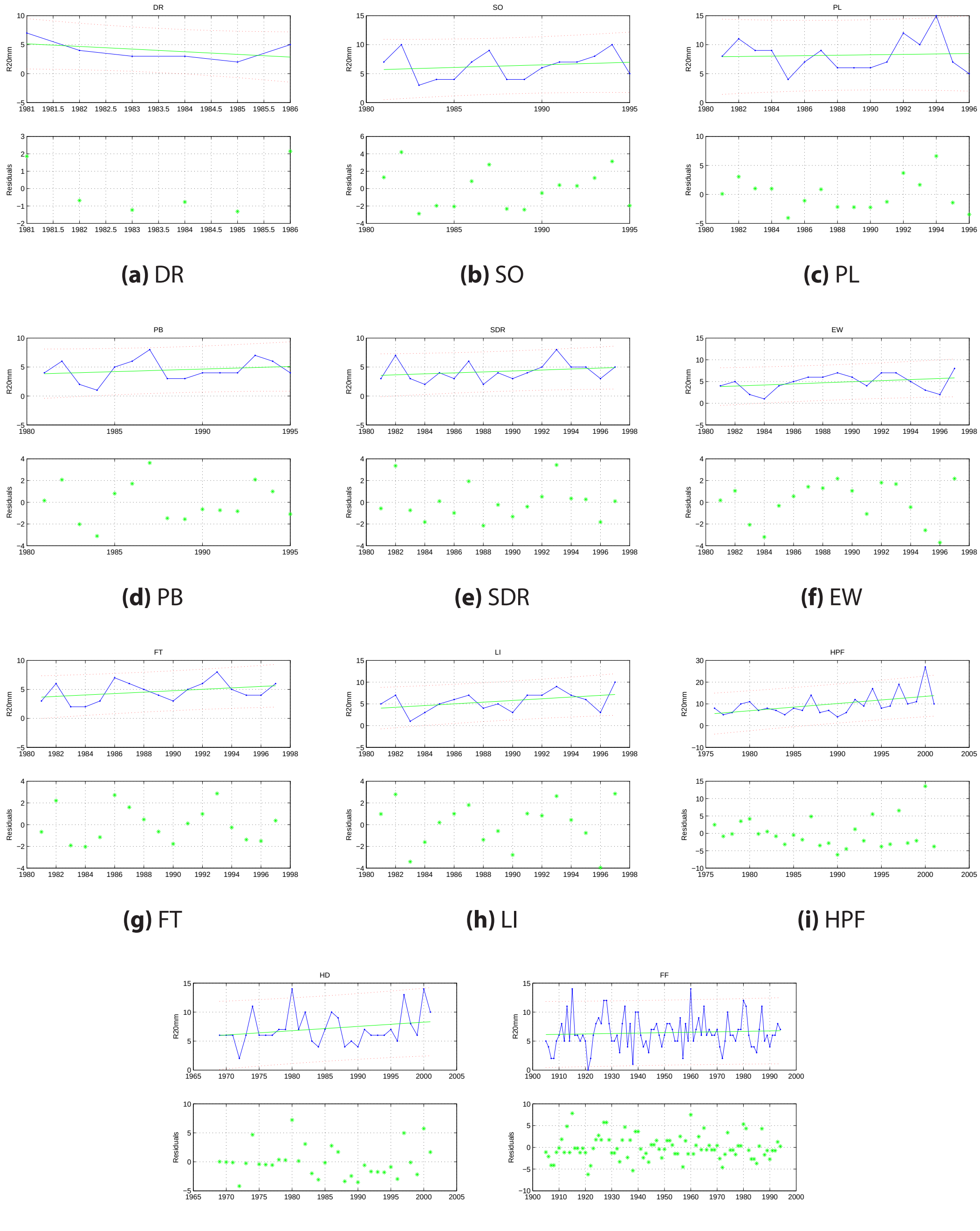


(j) HD



(k) FF

Figure A.9 Annual % of wet days with rainfall amount ≥ 10 mm at daily data stations



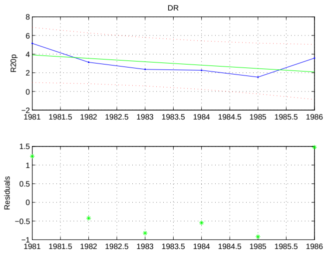
(a) DR **(b)** SO **(c)** PL

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

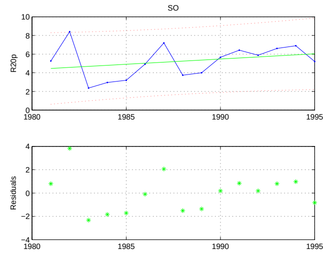
(g) FT **(h)** LI **(i)** HPF

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

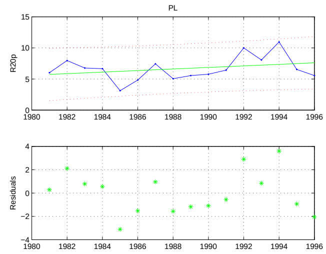
Figure A.10 Annual number of wet days with rainfall amount ≥ 20 mm at daily data stations



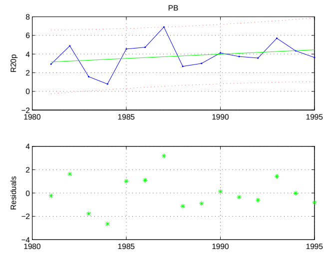
(a) DR



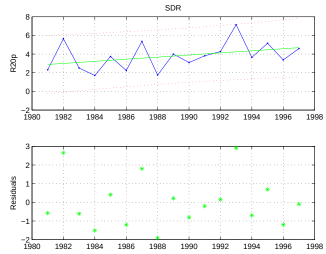
(b) SO



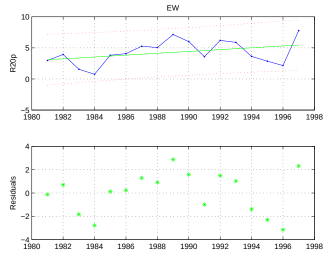
(c) PL



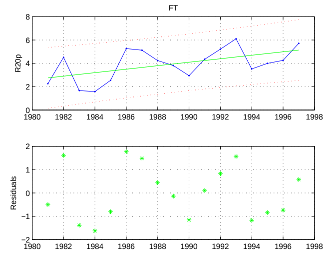
(d) PB



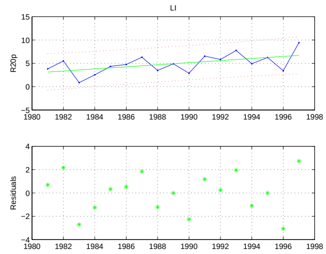
(e) SDR



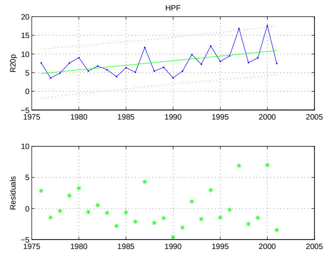
(f) EW



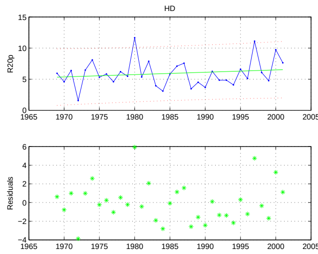
(g) FT



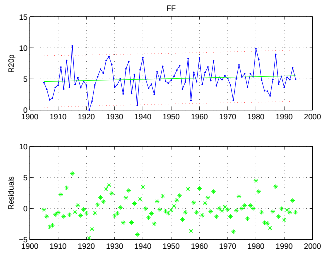
(h) LI



(i) HPF



(j) HD



(k) FF

Figure A.11 Annual % of wet days with rainfall amount ≥ 20 mm at daily data stations

A.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 A.12, Figure A.13 and Figure A.14, 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 A.13). The average intensity of the event was 18.1 mm/hr.

Rainfall Amount The observed mean monthly rainfall amount is shown in Figure A.15. 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 A.15).

Rainfall Duration The mean monthly rainfall duration is shown in Figure A.16. The mean monthly rainfall duration shows the similar characteristic October peak as the mean monthly rainfall amount.

Rainfall Intensity The maximum daily 1-min rainfall intensity series for Ditchling Road, Southover and Plumpton are shown in Figure A.14. The highest 1-min peak intensity reaching at 300 mm/hr was observed on 5 November 1991 at Ditchling Road (Figure A.14).

The mean monthly maximum 1-min rainfall intensity is shown in Figure A.17. 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 A.18. The highest values were observed in August, September and August at Ditchling Road, at Southover and Plumpton, respectively.

A.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 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

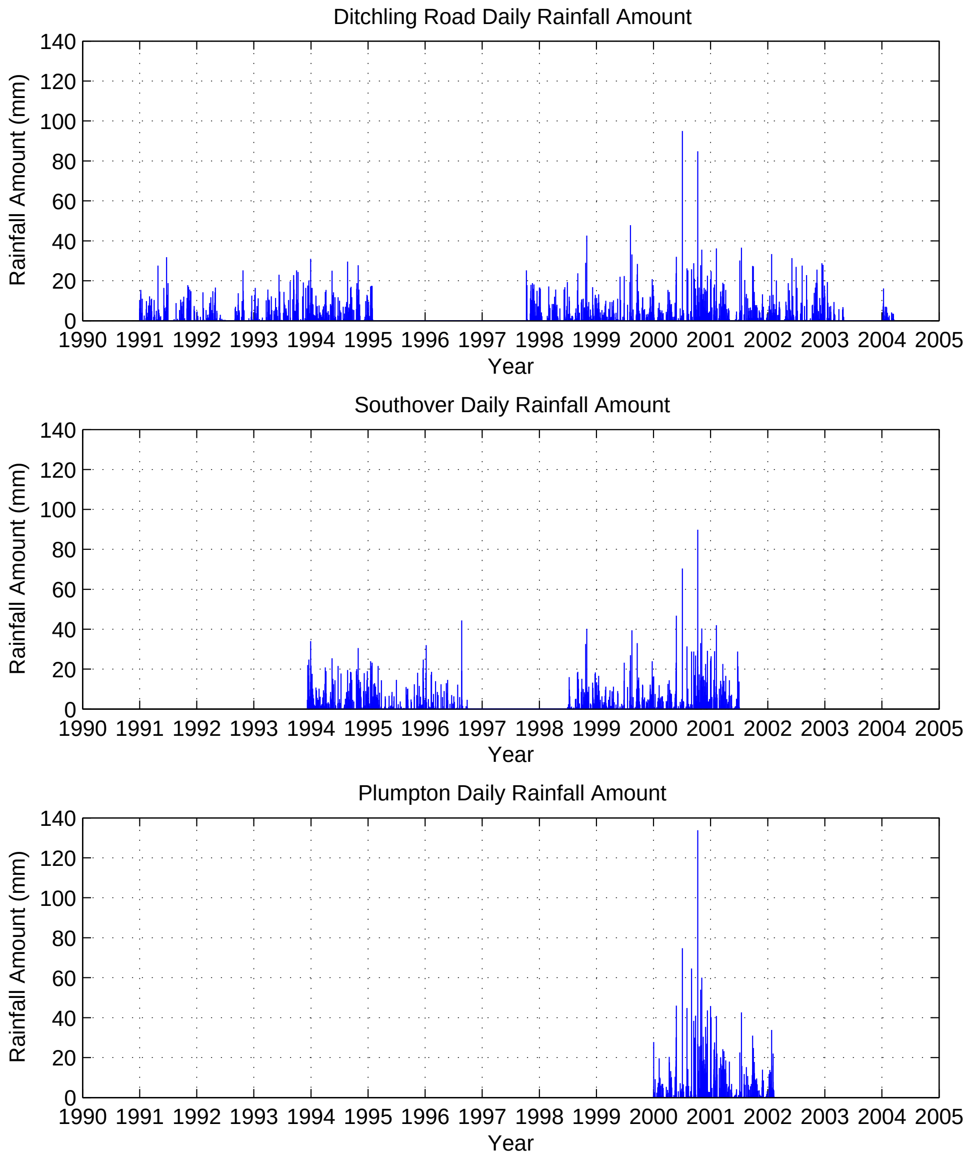


Figure A.12 Observed daily rainfall amount

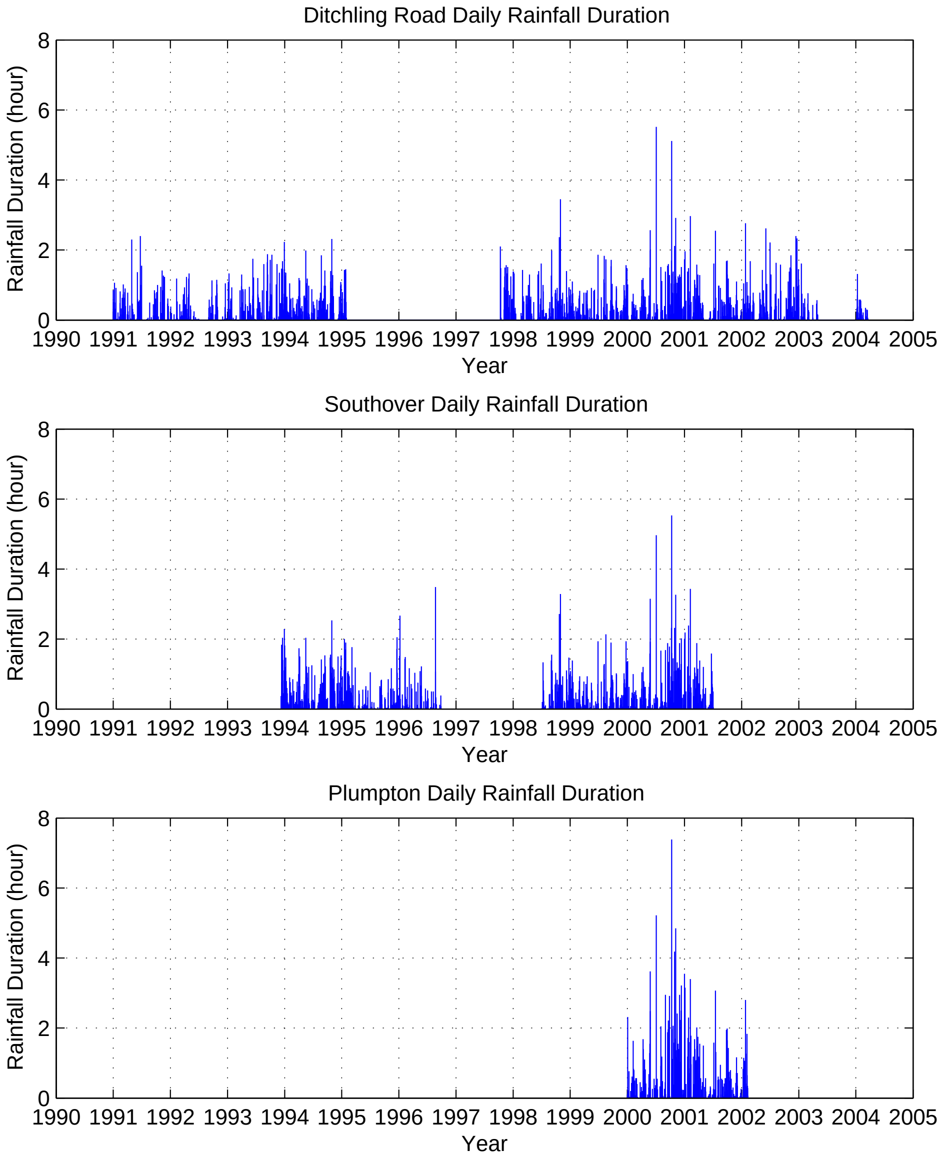


Figure A.13 Observed daily rainfall duration

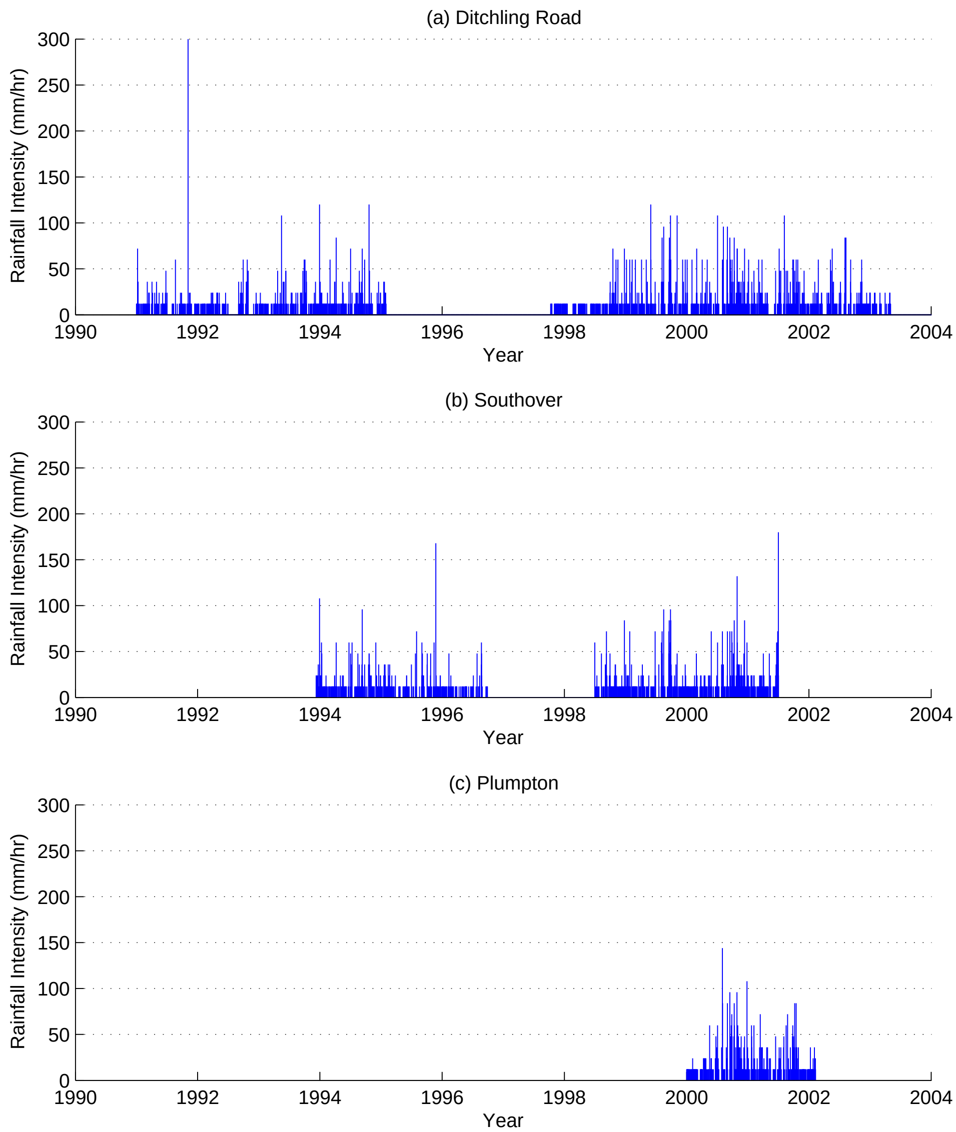


Figure A.14 Observed daily 1-min peak rainfall intensity.

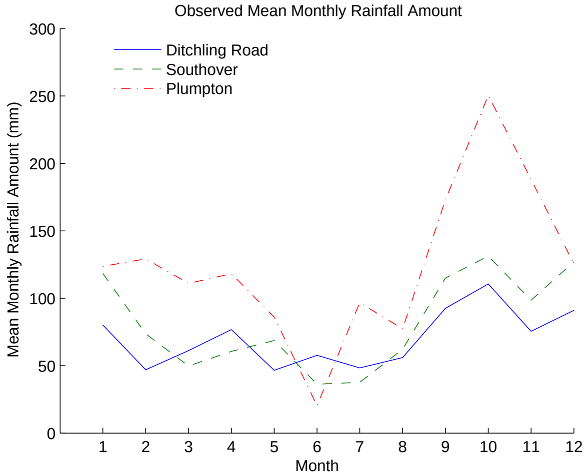


Figure A.15 Observed mean monthly rainfall amount

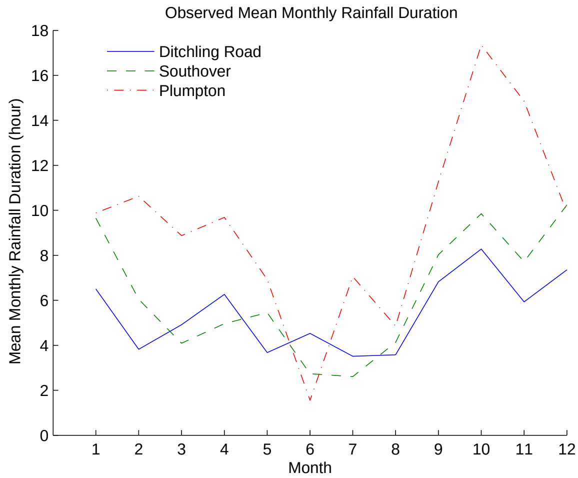


Figure A.16 Mean monthly rainfall duration

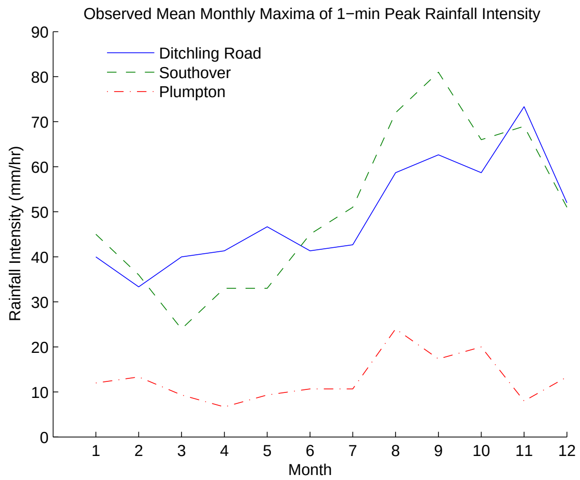


Figure A.17 Mean monthly maxima of 1-min peak rainfall intensity

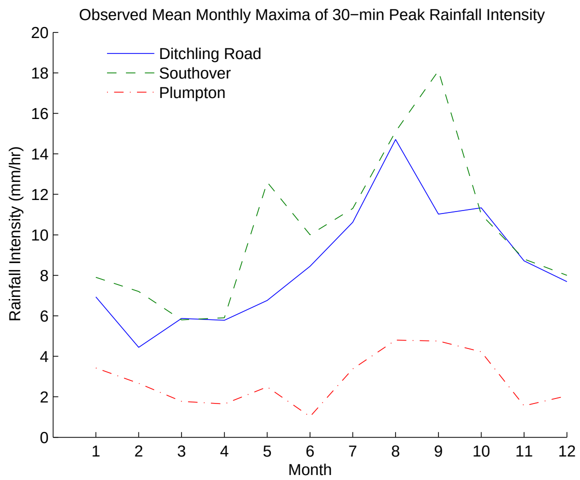


Figure A.18 Mean monthly maxima of 30-min peak rainfall intensity required to estimate soil erosion using the present process-based models such as ones like WEPP, EUROSEM and RillGrow which are used in this research.

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 dependent on one item of information, namely time. It is also important to note that as the intensity is time-dependent (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 A.17 and Figure A.18). 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 WSG 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 WSG using climate model predicted data. Therefore, future scenarios have been built and simulated future erosion with the continuous model (i.e. WEPP).

A.7 Conclusion

We know rainfall amounts are going to be change in the future, but what about intensity? Trenberth *et al.* (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 8.2).

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.

Appendix B

WEPP Input Data

B.1 Weather Input Data

B.1.1 For Temporal Scale Simulation

B.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
```

B.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
```

B.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
```

B.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
```

B.1.2 For Storm Patterns Simulation

B.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
```

B.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
```

B.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
```

B.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
```

B.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
```

B.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
```

B.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
```

B.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
```

B.1.3 For Continuous and Discontinuous Rainfall Simulation

B.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
```

B.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
```

B.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
```

B.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>
```

B.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 C

CLIGEN Input Data

C.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
```

C.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
```

Appendix D

EUROSEM Input Data

D.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)

D.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.

D.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.

D.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 E

RillGrow Input Data

E.1 Continuous and Discontinuous Rainfall

E.1.1 Continuous Rainfall

```
Units for time intervals (sec or min)              : min
Time/intensity (mm/hr) pairs                        : 0  240
                                                    : 3  240
                                                    : 6  240
                                                    : 9  240
                                                    : 12 240
                                                    : 15 0
```

E.1.2 Discontinuous Rainfall

```
Units for time intervals (sec or min)              : min
Time/intensity (mm/hr) pairs                        : 0  0
                                                    : 3  240
                                                    : 6  0
                                                    : 9  240
                                                    : 12 0
                                                    : 15 240
                                                    : 18 0
                                                    : 21 240
                                                    : 24 0
                                                    : 27 240
                                                    : 30 0
```

E.2 Within-Storm Intensity Pattern

E.2.1 Constant WSIP

```
Units for time intervals (sec or min)               : min
Time/intensity (mm/hr) pairs                        : 0   120
                                                    : 5   120
                                                    : 10  120
                                                    : 15  120
                                                    : 20  120
                                                    : 25  120
                                                    : 30  0
```

E.2.2 Increasing WSIP

```
Units for time intervals (sec or min)               : min
Time/intensity (mm/hr) pairs                        : 0   30
                                                    : 8   60
                                                    : 16  90
                                                    : 20  180
                                                    : 24  270
                                                    : 28  360
                                                    : 30  0
```

E.2.3 Decreasing WSIP

```
Units for time intervals (sec or min)               : min
Time/intensity (mm/hr) pairs                        : 0   360
                                                    : 2   270
                                                    : 6   180
                                                    : 10  90
                                                    : 14  60
                                                    : 22  30
                                                    : 30  0
```

E.2.4 Increasing-Decreasing WSIP

```
Units for time intervals (sec or min)               : min
Time/intensity (mm/hr) pairs                        : 0   30
                                                    : 4   60
                                                    : 8   90
                                                    : 10  180
```

```
                                                    : 12 270
                                                    : 14 360
                                                    : 16 270
                                                    : 18 180
                                                    : 20 90
                                                    : 22 60
                                                    : 26 30
                                                    : 30 0
```

E.3 Other Inputs

```
Duration of rain/duration of simulation (sec or min)  : 30 45 min
Save interval (sec or min) : 0.25 0.5 1 2.83 3 3.16 7.83 8 8.16 12.83 13 13.16
17.83 18 18.16 22.83 23 23.16 27.83 28 28.16 30 35 40 min
Random number seed                                    : 27853
Files to output                        [see codes.txt]: de sr ts tr ad rt fr re
tc as sc as ak sp st td tn
Output file names            [omit path and extension]: x11
Variable report level/start/finish     [see codes.txt]: 0
Input/output as Idrisi, Idrisi-32, ArcView? [i i32 av]: i32
Output in binary or ascii?                       [b a]: b
Include dummy border in output files?                 : n
Output splash efficiency check file?                  : y

; Run-time graphics ------------------------------------------------------------
Run type    [0=silent 1=normal 2=minimized 3=graphics]: 3
   If graphics, rotate 90 degrees?                    : y
   Code for data item to graph         [see codes.txt]: 6
   Data value which will be min. colour               : 0
   Data value which will be max. colour               : 15
   Palette file                  [Idrisi .pal or .smp]:/program
files/idrisi32/symbols/watr256.smp

; Microtopography --------------------------------------------------------------
Microtopography file                   [path and name]: in/leics/x11/11dini10
Edges bounded                                   [tlrb]: tlr
Datum elevation to be added (mm)                      : 0
Slope angle to be added (%)                           : 26.8
Effective edge angle (%)      [0=use overall gradient]: 0

; Rainfall ---------------------------------------------------------------------
Mean rainfall intensity (mm/hr) or time-series file   : rain_time_series.dat
Standard deviation of rainfall intensity (mm/hr)      : 6.25
Mean raindrop diameter (mm)                           : 2.0
Standard deviation of raindrop diameter (mm)          : 0.2
File for rainfall variation               [blank=none]:
in/leics/intensity/intens10

; Splash redistribution --------------------------------------------------------
Calculate splash redistribution?                      : y
```

```
   Interval between splash calculations (sec)         : 0.5
   Splash efficiency data file (path and name)        : splash_eff.ini
   Constant n for splash efficiency (sec**2/mm)       : 30000
   Couple splash and flow?                            : y

; Run-on ----------------------------------------------------------------------
Run-on from above top of slope?                       : y
   Length of run-on area (mm)                         : 710
   Rain intensity multiplier for run-on area          : 0.85
   Flow speed on run-on area (mm/sec)                 : 30

; Infiltration ----------------------------------------------------------------
Infiltration rate (mm/hr)                             : 0

; Overland flow ---------------------------------------------------------------
Maximum instantaneous kinematic flow speed (mm/sec)   : 1200
Within-cell roughness                                 : 0.0078
Exponent n                                            : 0.5

; Rill detachment -------------------------------------------------------------
Calculate rill erosion?                               : y
   Bulk density of soil (t/m**3)                      : 1.3
   Constant k for detachment (kg/m**3)                : 0.078
   Constant T for detachment (Pa)                     : 3000   ; 1100 Nearing
orig
   Coefficient of variation of T for detachment       : 0.4
   Coefficient of variation of tau for detachment     : 0.4
   Allow edges to erode?                              : n
      Diff in plot end elev (below lowest point) (mm) : 13

; Transport capacity ----------------------------------------------------------
   Constant alpha for transport                       : -34.47
   Constant beta for transport                        : 38.61
   Constant gamma for transport                       : 0.845
   Constant delta for transport                       : 0.412

; Deposition ------------------------------------------------------------------
   Instantaneous maximum sediment concentration (%)   : 20
   Threshold Reynolds number for laminar flow         : 500
   Constant C1 at laminar threshold (sec**-1)         : 50
   Threshold Reynolds number for turbulent flow       : 2000
   Constant C1 at turbulent threshold (sec**-1)       : 5
   Exponent n                                         : 6

; Various physical constants --------------------------------------------------
Density of water (t/m**3)                             : 1
Kinematic viscosity of water (m**2/sec)               : 1e-6
Gravitational acceleration (m/sec**2)                 : 9.81
```