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

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

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

## 1.2 Soil Erosion Processes

### 1.2.1 Introduction

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

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

Soil erosion problems can be viewed in three different ways (Kirkby and Morgan, 1980). Firstly, in the broadest view, soil erosion can be compared with other processes of landscape denudation. When and where it is the most rapid process, soil erosion should be recognised as the dominant problem. This view leads to the question of what erosion rates can be tolerated in the long-term. Secondly, a narrower overview examines soil erosion with its immediate climatic and vegetational controls. This then leads to the question as to how well the processes involved in raindrop impact, flow generation, and sediment resistance are understood. Thirdly, soil erosion can be considered in relation to its broad patterns in time and space. Yet, the reasons for the temporal and spatial distributions of soil erosion are only partially understood (Quine and Zhang, 2002; Gómez *et al.*, 2005; Wakiyama *et al.*, 2010).

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

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

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

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

### 1.2.2 Rainfall

#### 1.2.2.1 Raindrop Splash

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

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

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

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

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

#### 1.2.2.2 Rainfall Intensity

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

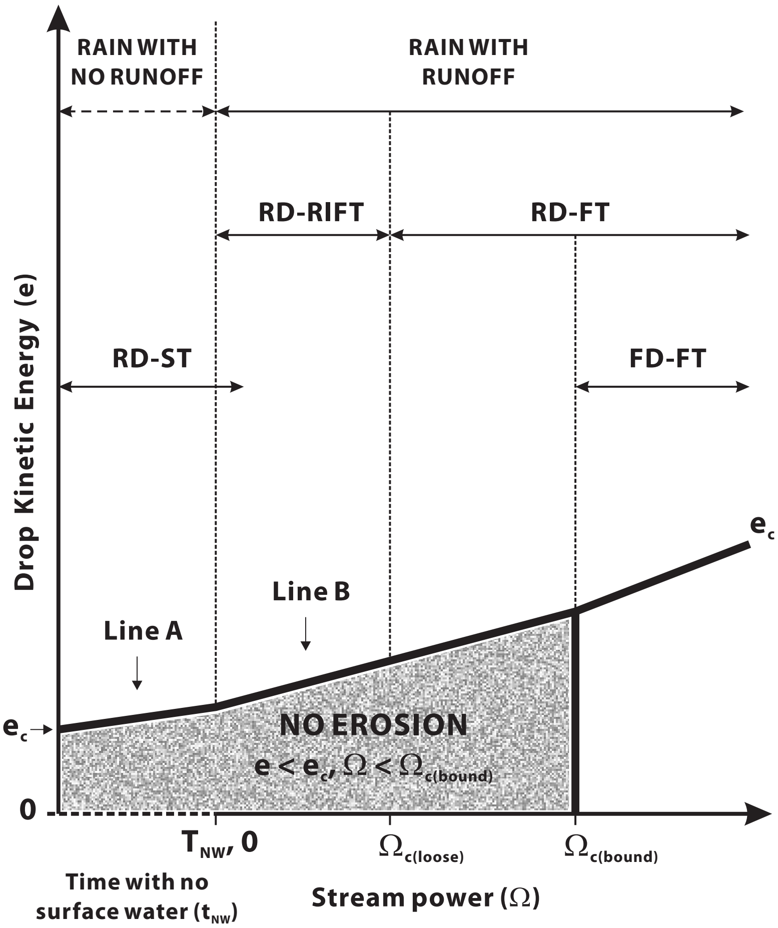



**Figure 1.1** Detachment and transport processes associated with variations in raindrop and flow energies. $T_{NW}$: total time when rain falls and there is no surface water. $e_c$: critical raindrop energy to cause detachment; raindrop-induced erosion occurs when drop energy is equal or greater than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

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

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

Parsons and Stone (2006) ran a laboratory-based rainfall simulation experiment to determine the implications of temporal variation of rainfall intensity for rates of soil loss. He found that erosion is least for the constant-intensity storms. This is highly significant because soil-erosion models are typically calibrated using data obtained from constant-intensity experiments. Moreover, storm pattern does not appear to affect the volume of runoff, but it does affect the quantity of eroded sediment. In particular, the constant-intensity storm patterns are associated with low erosion rates. Storm pattern also affects the size-distribution of the eroded sediment. Parsons and Stone (2006) therefore concludes that the relationship between rainfall energy and interrill erosion is more complex than is currently assumed in process-based models of soil erosion.

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

### 1.2.3 Soil Type

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

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

Sandy soils are however more erodible than clayey soils because the aggregates of these sandy soils slake more readily and seal the soil surface (LeBissonnais, 1996). Loamy soils are also particularly at risk of sealing (Ramos *et al.*, 2000).

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

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

### 1.2.4 Topography

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

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

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

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

### 1.2.5 Land Use

Soil erosion potential is highest where the soil has no or very little vegetative cover. Vegetation cover protects the soil from direct raindrop impact and splash, and tends to slow down surface runoff. On a field with complete vegetation cover, runoff and erosion are comparatively small, often less than 5% of runoff and 1% of erosion from bare soil, respectively (Braskerud, 2001; Rey, 2003). One reason is because the infiltration rates of the vegetated field are relatively higher than those on bare soils as the field often has a better soil structure and more stable aggregates (Robinson and Phillips, 2001). When runoff does take place, the leaves and roots of plants inhibit the flow by reducing the velocity of the flow (Braskerud, 2001; Rey, 2003). On soils with less than 70% vegetation cover, runoff and erosion increase rapidly when rainfall occurs (Favis-Mortlock and Savabi, 1996). Under less than 20–30% vegetation cover, runoff and erosion are related to the amount of bare ground, increasing as the proportion of bare ground increases (Favis-Mortlock and Savabi, 1996).

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

## 1.3 Soil Erosion and Rainfall Intensity

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

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

Substantial rills or gullies were formed by the rainfall event on 7 October 1987. As a result of this, following rainfalls as low as 7 mm caused runoff and erosion (Boardman, 1988). Although there are no event-by-event records available for soil losses, it is evident that the rainfall on 7 October 1987 played an important role, by contributing to rill or gully generation, on soil erosion in the area. However, the main factors responsible for the severe erosion were land use and farming practices.

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

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

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

**Northern Ethiopia Highlands, 1998-2000 (Nyssen *et al.*, 2005)** Rainfall intensity in Northern Ethiopia Highlands was monitored using a tipping bucket rain gauge during 1998-2000 (Nyssen *et al.*, 2005). Overall rain intensity in the area is low. 88% of total rain volume falls with an intensity <30 mm/h. Most storms have a low intensity with a brief high intensity part. This high intensity can be observed at the beginning, in the middle or at the end of the storm. Although area-averaged intensity was low in this area, it was found that maximum rain intensity at individual locations exceeded by far the threshold values for excessive rain (see Table 5, Nyssen *et al.*, 2005). Rainfall intensities beyond these thresholds were known to cause >50% of total soil losses (Krauer, 1988). Large rain erosivity in the area is due to larger median volume drop diameters ($D_{50}$) than those reported for other regions of the world, rather than due to high intensity.

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

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

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

Extensive erosion of top soil occurred, followed by the development of gullies and rills by overland flow during the storm. Approximately 790 t of sediment was eroded from the two fields excluding the sediment that reached nearby river (River Avon, UK). Average sediment yields was 49.7 t/ha which is equivalent to the average ground lowering of 3.8 mm.

## 1.4 Rainfall Intensity and Climate Change

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

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

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

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

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

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

In order to run a soil erosion model such as WEPP (Water Erosion Prediction Project, See Section 1.5.3 for more details), for example, various weather parameters for each day of the simulation period are required (Flanagan and Nearing, 1995). These weather variables (e.g. rainfall depth and duration, peak storm intensity and time to peak, minimum and maximum temperatures, dew point temperature, solar radiation, wind speed and direction) can either be generated by CLIGEN (CLImate GENerator, See Section 1.5.3.1 for more details) or compiled manually from observed climate data.

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

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

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

1. Regional precipitation error spanned a wide range, with values as extreme as approximately −90% or +200%.
2. Simulated precipitation sensitivity to doubled $CO_2$ was mostly in the range of −20% to +20% of the control value.
3. Overall, the precipitation errors were greater than the simulated changes. It can be expected that, due to relatively high temporal and spatial variability in precipitation, temperature changes are more likely to be statistically significant than precipitation changes.

## 1.5 Soil Erosion Prediction Models

### 1.5.1 Introduction

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

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

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

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

**Table 1.1** Types of models (from Morgan, 1995)

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

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

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

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

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

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

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

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

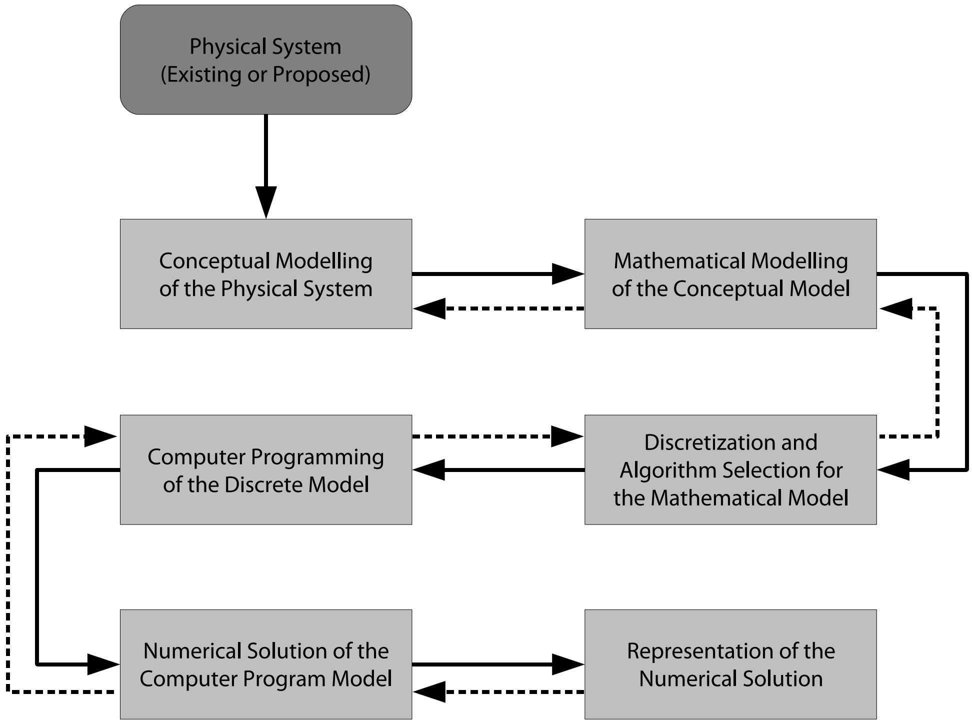



**Figure 1.2** Proposed phases for computational modelling and simulation. (From Oberkampf *et al.*, 2002)

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

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

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

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

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

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

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

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

### 1.5.2 Universal Soil Loss Equation (USLE)

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

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

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

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

The rainfall erosivity factor ($R$) is related to the raindrop impact effect. $R$ factor provides relative information on the amount and rate of runoff associated with the rain. The soil erodibility factor ($K$) is used to represent the differences of natural resistances of soils to erosion. The slope length ($L$) and steepness($S$) factors provide the topographic information that can affect the rate of energy dissipation. The cropping factor ($C$) is the ratio of soil loss from cropped field under specific conditions to the corresponding loss from tilled, continuous fallow conditions. The conservation practice factor ($P$) is the ratio of soil loss with a specific conservation practice to the corresponding loss with conventional slope tillage.

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

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

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

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

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

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

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

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

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

### 1.5.3 Water Erosion Prediction Project (WEPP)

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

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

The steady state erosion component of WEPP is based on:

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

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

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

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, $\tau_f$ is flow shear stress acting on soil particles, and $\tau_c$ 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, $\sigma_{ir}$ is the interrill runoff rate, $SDR_{RR}$ is the sediment delivery ratio, $F_{\text{nozzle}}$ is an adjustment factor to account for sprinkler irrigation nozzle impact energy variation, $R_s$ is the rill spacing, and $\omega$ is the width. Interrill erosion is also expressed with baseline interrill erodibility as (Nicks, 1998):

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

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

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

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

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

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

#### 1.5.3.1 CLIGEN

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

In comparison to other climate generators, CLIGEN is better at preserving the low-order statistics of rainfall, temperature, and solar radiation on a daily, monthly, and annual basis (Nicks *et al.*, 1995). Unique to CLIGEN is the capacity to simulate the three additional weather variables to characterize the storm pattern, namely storm duration, time to peak, and peak intensity, which are specifically developed for the WEPP simulation (Flanagan and Nearing, 1995).

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

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

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

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

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

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

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

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

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

### 1.5.4 European Soil Erosion Model (EUROSEM)

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

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

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

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

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

The flow chart for EUROSEM is shown in Figure 1.3.

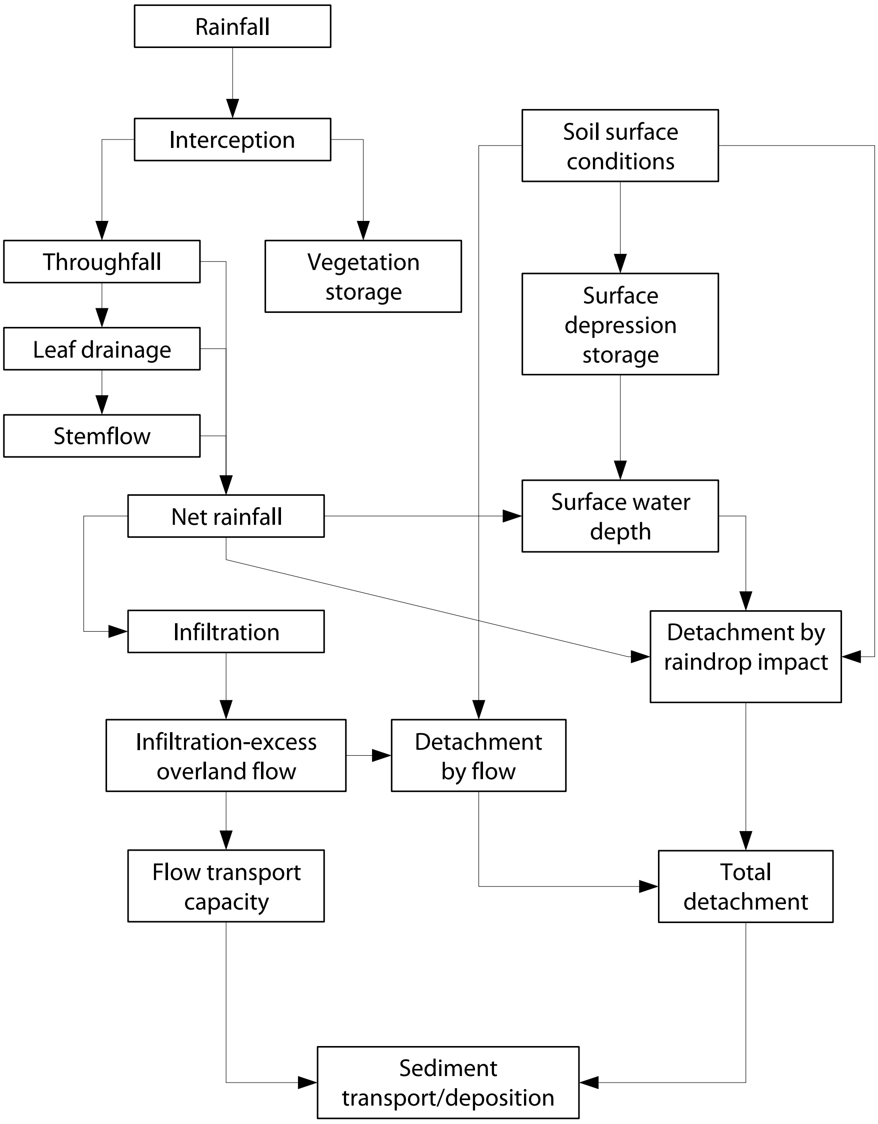



**Figure 1.3** Flow chart of EUROSEM (from Morgan *et al.*, 1998)

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

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

where $C$ is sediment concentration (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 ($m^3/J$), $\rho_s$ 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/m²), $z$ 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, $\beta$ 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 $\omega$ is unit stream power (cm/s) which is defined as $\omega = 10vs$ ($v$ = mean flow velocity (m/s) and $s$ = slope (%)), $\omega_c$ is a critical value of unit stream power (0.4 cm/s), and $c$ and $\eta$ 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, $\rho_s$ is the sediment density (Kg/m$^3$), $\Omega$ is Bagnold's modified stream power, $\Omega_c$ is a critical value of Bagnold's modified stream power, $n$ is Manning's $n$, and $\kappa = 5$. Sediment delivery to the rills is simulated depending on the transport capacity of the interrill flow.

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

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

After personal communication (16 Jun 2004) with Anthony J. Parsons , it is noted that EUROSEM may have a unit conversion error. The model document states that the flow depth ($h$) in equation 1.11 is in metres. However, a study by Torri *et al.* (1987) on which this equation is based indicates that the height is in millimetres (see Figure 2 in Torri *et al.* (1987)). Anthony J. Parsons suggests that the height is in centimetres rather than either metres or millimetres. If confirmed, this error would have major effects on EUROSEM's ability to estimate runoff and erosion.

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

### 1.5.5 RillGrow

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

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

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

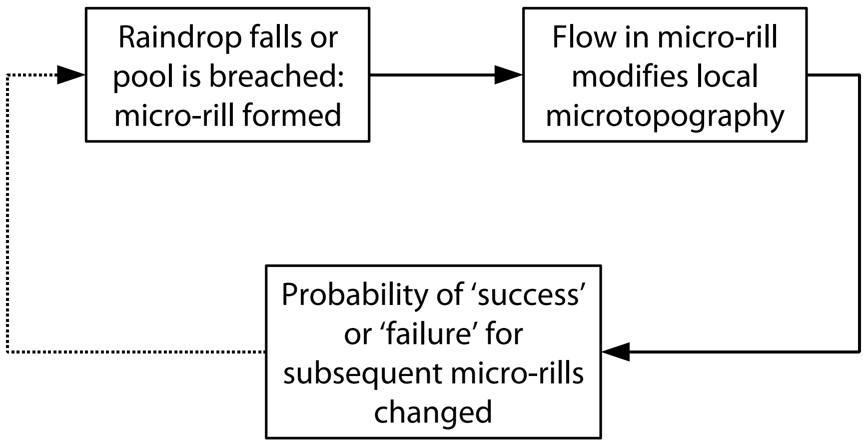



**Figure 1.4** The conceptual feedback loop of RillGrow (From Favis-Mortlock, 1998*b*)

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

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

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

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

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

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

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

For each iteration:

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

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

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

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

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

(Favis-Mortlock, personal communication 2006).

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

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

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

# Chapter 2

# RESEARCH BACKGROUND AND OBJECTIVES

## 2.1 Background and Direction

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

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

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

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

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

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

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

## 2.2 Objectives and Rationales

The main objective of this research is to investigate:

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

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

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

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

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

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

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

A primary purpose of these erosion models (i.e. WEPP, EUROSEM and RillGrow) is to simulate soil erosion. Even though each model has its unique way of simulating erosion processes, the main design purpose is the same; to simulate the real-world erosion processes. Erosion models are developed in order 1) to use them as important predictive tools for future or unmonitored landscapes; 2) to study how different factors play a role in erosion; 3) to understand erosion processes; and in turn, 4) to minimise environmental issues caused by soil erosion. Because of these purposes, *ideally* all erosion models should be based on similar understanding of erosion, and simulate erosion similarly. This general idea was taken into account and it was hypothesised that the models selected for this research produce similar results when a given rainfall intensity was applied to them. Yet, the reality is somewhat different from the ideal, and one may still expect that the models may produce divergent responses (Favis-Mortlock, 1998*a*; Jetten *et al.*, 1999). However, it is important to investigate this diversity of model outputs in order to identify and improve areas where our understanding is limited.

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

The above statement by Karlin highlights one of reasons why many models are used in numerical and analytical studies. In most cases, a model is based on knowledge that is limited by what we already know about the process. There can be a range of different understandings of the same processes—soil erosion processes in this case. These understandings are expressed as mathematical equations, and then translated into computing languages, and finally put together as a model with which our understandings of the processes can be tested. This provides us with a complete control over affecting parameters. Generally, it is not possible to gain complete control over affecting factors with field experiments or with laboratory experiments because modifying only one factor without altering other factors is not feasible. Using a model, an individual input parameter may be isolated, adjusted and investigated to find its effects on the overall erosion process, while keeping all the remaining parameters constant. Of course, this still does not guarantee a correct prediction by the model. However, this kind of approach helps to "sharpen the questions". More focused questions from modelling studies may help to fill out, or rather to pinpoint the gap in our understanding of the processes. There have been several studies employing this type of approaches already (Favis-Mortlock and Boardman, 1995; Favis-Mortlock and Guerra, 1999; Pruski and Nearing, 2002*b*; Nearing *et al.*, 2005).

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

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

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

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

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

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

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

## 2.3 Some Questions To Be Answered

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

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

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

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

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

## 2.4 Expected Outcomes

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

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

# Chapter 3

# DESCRIPTIONS OF DATA, MODELS AND METHODS

## 3.1 Data

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

### 3.1.1 Rainfall Data

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

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

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

**Table 3.1** Precipitation data used in this study

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

† Aggregated 1-min data originally from tipping bucket data

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

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

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

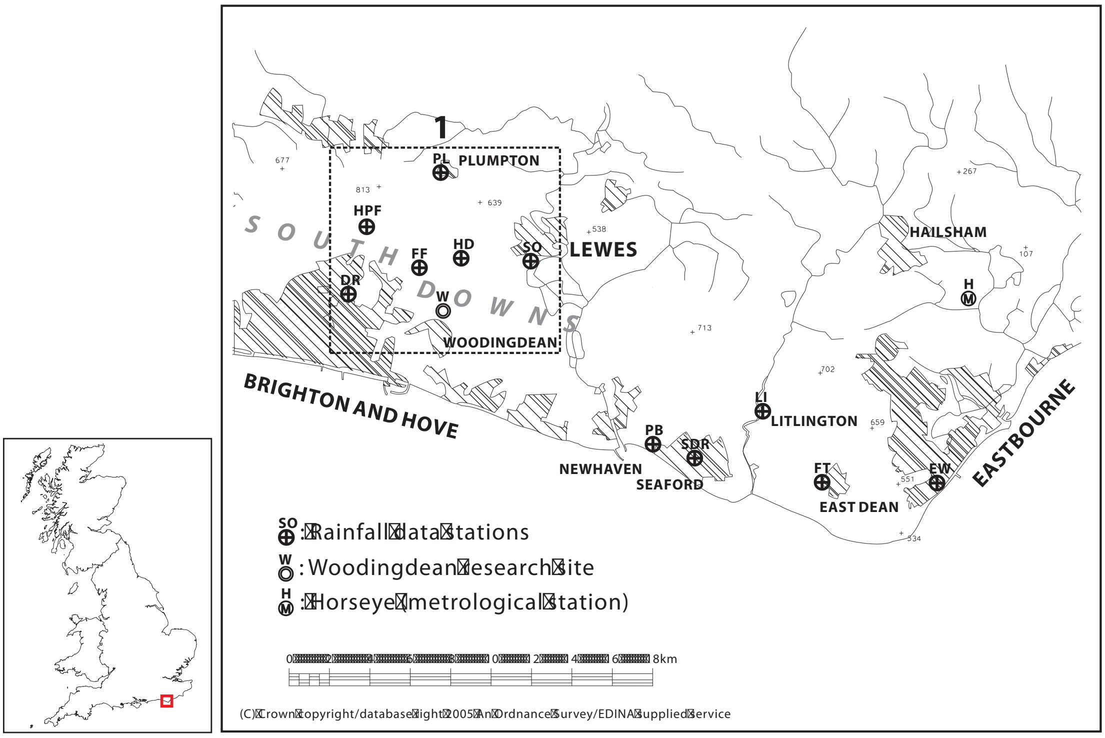



**Figure 3.1** Locations of daily rainfall data stations. DR: Ditchling Road, SO: Southover, PL: Plumpton, SDR: Seaford D. Road, EW: Eastbourne Wilm., FT: Friston Tower, LI: Litlington, PB: Poverty Bottom, HPF: High Park Farm, HD: Housedean, FF: Falmer Farm, W: Woodingdean (soil, slope, crop management),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

**Table 3.2** Details of rainfall data stations

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

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

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

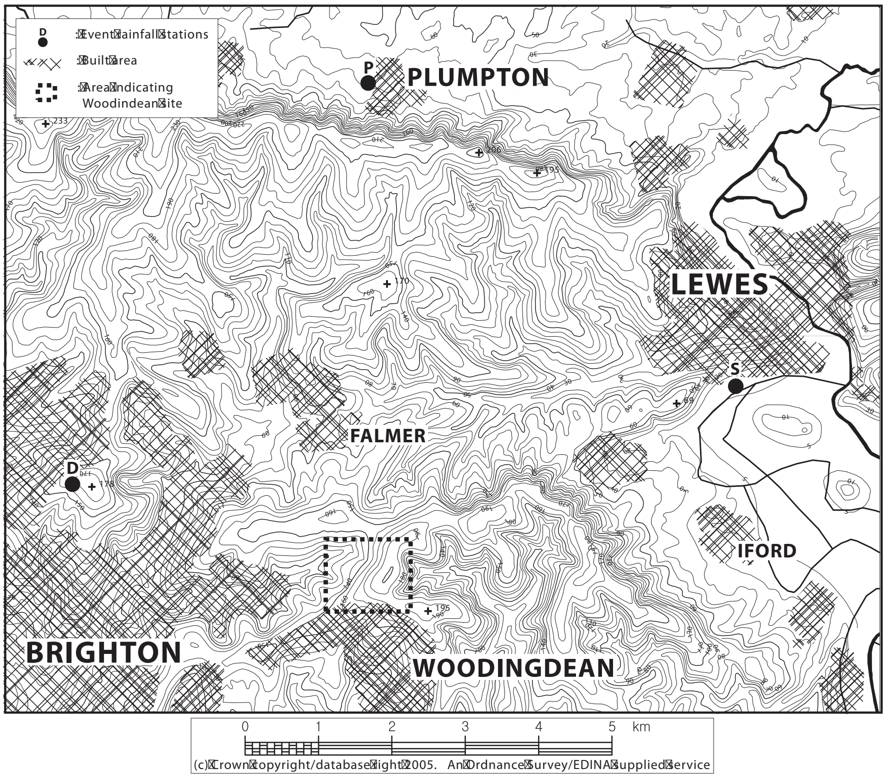



**Figure 3.2** Locations of event rainfall data stations. *filled circles*: event rainfall data stations (S: Southover, D: Ditchling Road, P: Plumpton); Woodingdean site is indicated by *dotted frame* (see Figure 3.3 for the detail)

## 3.1.2 Other Data

### 3.1.2.1 Soil

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

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

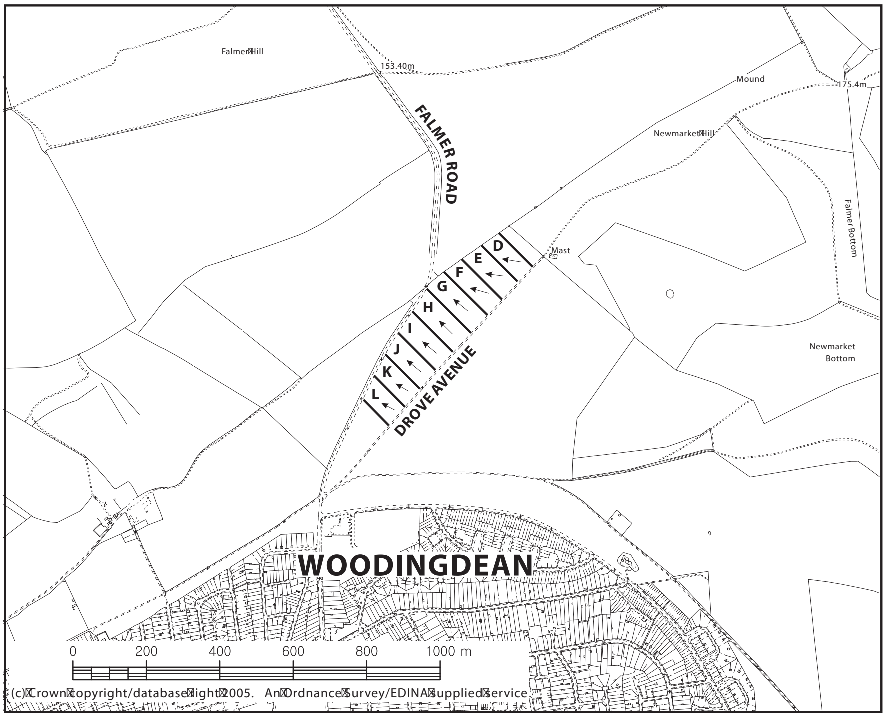



**Figure 3.3** Woodingdean site. The arrows indicate approximate downslope direction. Each letter (D-L) denotes hillslope profiles used for model simulations.

The soil in the area is shallow (around 20 cm to chalk) and stony silty rendzina of the Andover series (Jarvis *et al.*, 1984). The Andover silt loams of the South Downs are both stony and prone to crusting. All the soil input parameters are summarised in Table 3.3 and Table 3.4.

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

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

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

#### 3.1.2.2 Management

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

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

| | Uncalibrated Hydrological and erosional parameters | Calibrated Hydrological and erosional parameters |
|---|---|---|
| Effective hydraulic conductivity of top soil layer (mm/hr) | 2.1[a] | 3.0[a] |
| Interrill erodibility $K_i$ (kg s/m$^4$) | 5502700 | 2000000 |
| Rill erodibility $K_r$ (s/m) | 0.0871 | 0.0050 |
| Critical shear stress $\tau_c$ (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 $\tau_c$

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

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

#### 3.1.2.3 Topography

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

#### 3.1.2.4 Temperature

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

## 3.2 Justification for Erosion Model Selection

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

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

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

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

**Table 3.6** Summary of the erosion models used in this research

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

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

## 3.3 A Brief Overview of Research Method

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

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

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

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

- number of raindays with rainfall amount ≥20 mm.

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

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

### 3.3.1 Statistical Methods for Trend Investigation

Statistical methods used in this research are briefly summarized here.

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

**Mann-Kendall's Test** Mann-Kendall's test is a non-parametric test for the detection of trend in a time series. This is primarily used because it has no linearity assumption. Since the first proposals of the test by Mann (1945) and Kendall (1975), covariances between Mann-Kendall statistics were proposed by Dietz and Killeen (1981) and the test was extended in order to include seasonality (Hirsch and Slack, 1984), multiple monitoring sites (Lettenmaier, 1988) and covariates representing natural fluctuations (Libiseller and Grimvall, 2002).

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

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

## 3.4 Observed Rainfall Characteristics Of The Study Area

### 3.4.1 Introduction

As stated previously, it became apparent at the early stage of this research that RCM rainfall data could not (and still cannot) be used directly for erosion simulations. Although RCMs and empirically downscaled data from GCMs allow projections to be made at a finer scale than GCMs, RCM projections still vary greatly between models in the same way as GCMs and empirical downscaling does not attempt to correct any biases in the data from the GCMs. Even with a finer scale than GCMs, RCM data do not hold sufficiently detailed information of rainfall intensity that can be used directly for erosion simulations, and were not reliable enough for this type of approach yet—and still they are not (Nearing, 2001; Michael *et al.*, 2005; O'Neal *et al.*, 2005). That is why this part of research was carried out.

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

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

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

### 3.4.2 Method

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

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

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

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

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

**Table 3.7** Rainfall intensity indicators

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

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

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

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

**Table 3.8** Daily Rainfall Stations and Record Details

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

* ( ): Number of years

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

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

### 3.4.3 Monthly Precipitation

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

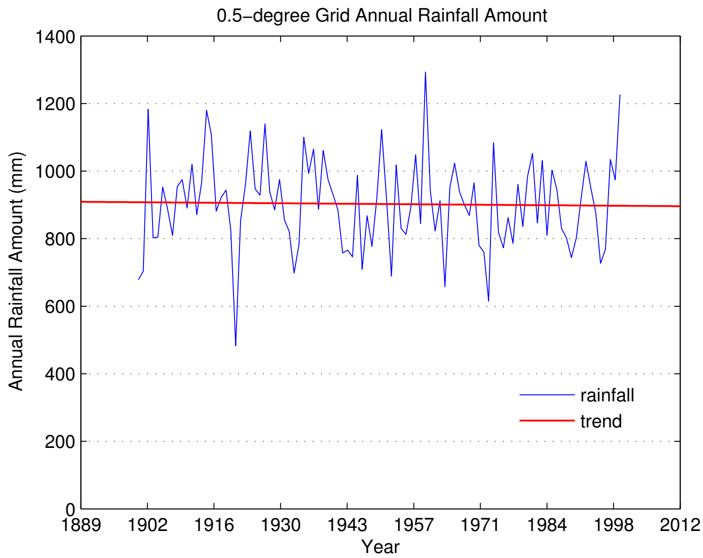
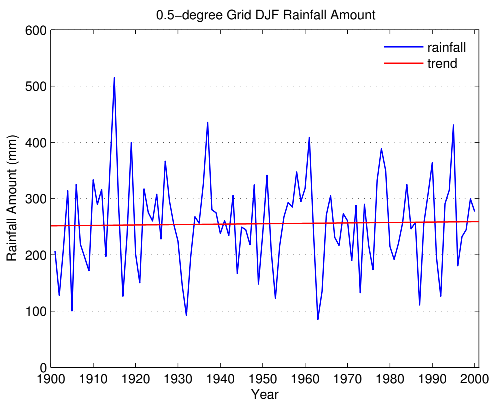



**Figure 3.4** Annual rainfall amount trend of monthly grid data

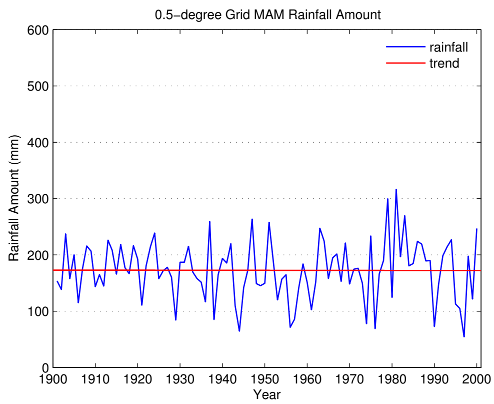
There is no statistically significant trend in seasonal rainfall amounts (Figure 3.5).

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

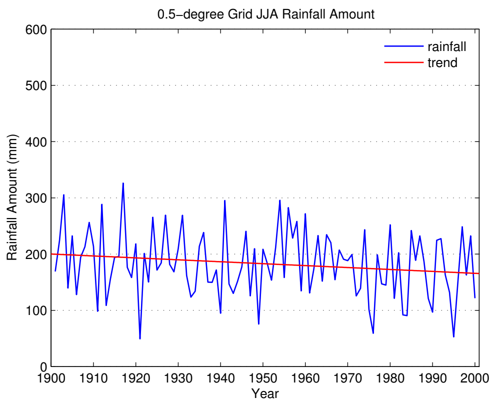
Rainfall amounts in July have a decreasing trend throughout the whole data period (1901–2000) (Figure 3.7).



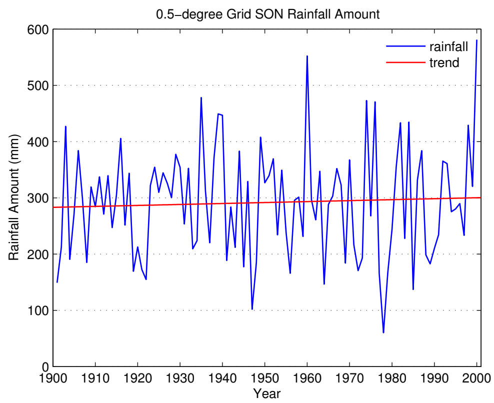

**(a)** DJF




**(b)** MAM




**(c)** JJA




**(d)** SON

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

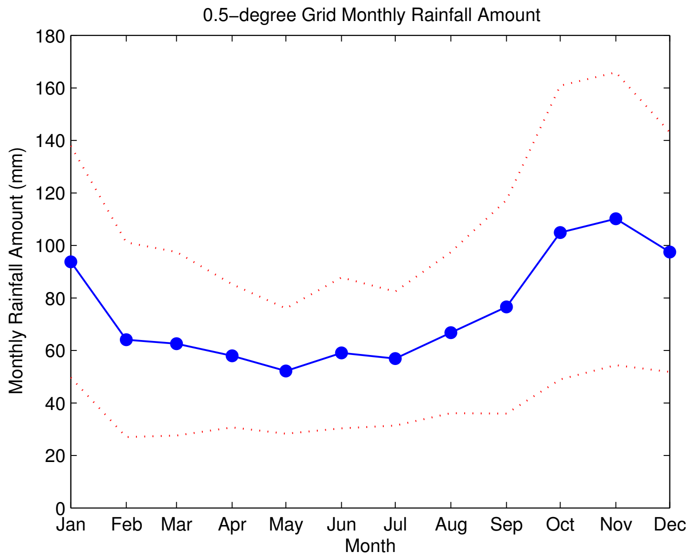



**Figure 3.6** Average monthly rainfall patterns of monthly grid data. Dotted lines indicate standard deviation with 95% confidence level.

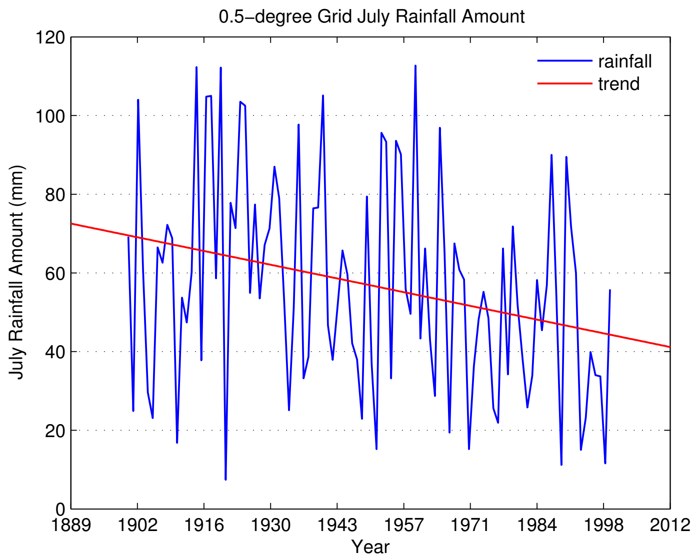



**Figure 3.7** July rainfall amount trend over 1901-2000

### 3.4.4 Daily Precipitation

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

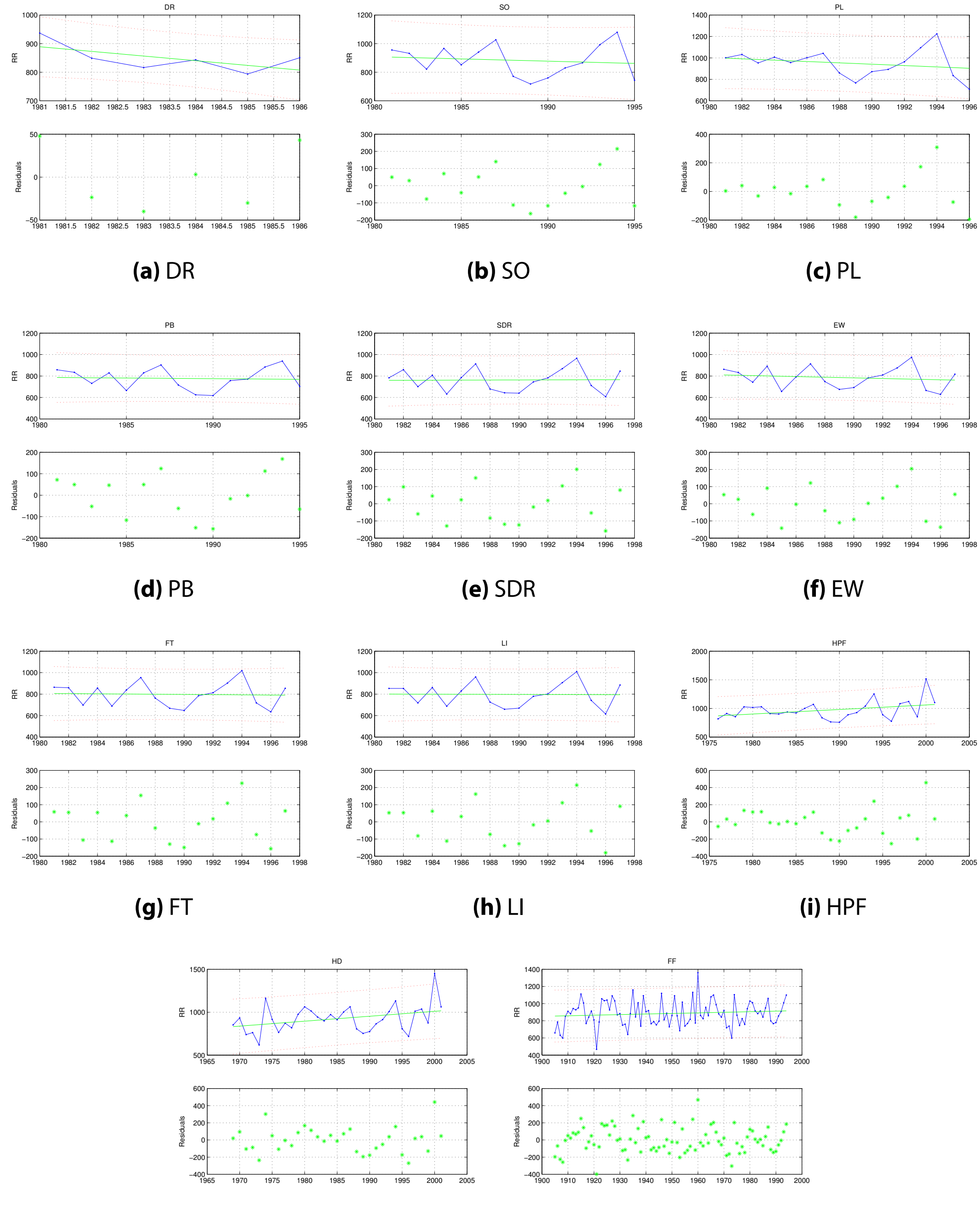
**Rainfall Amount (RR)** All the station show no statistically significant trend in annual rainfall amount. This result agrees with that of monthly 0.5° grid rainfall data.

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

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

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

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



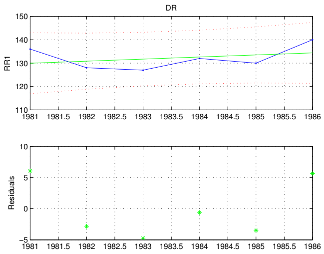
**(a)** DR **(b)** SO **(c)** PL

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

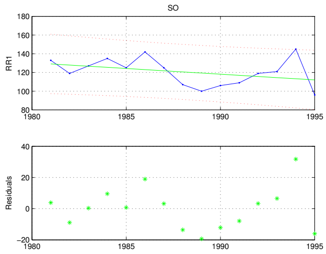
**(g)** FT **(h)** LI **(i)** HPF

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

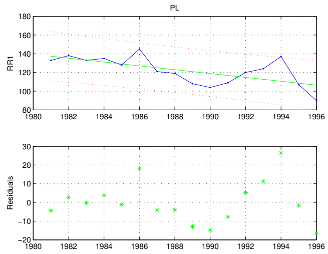
**Figure 3.8** Trends of annual rainfall amount (RR) at daily data stations



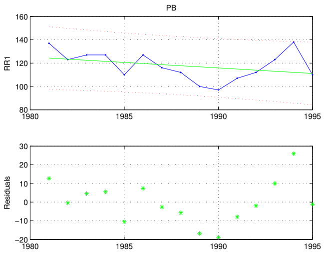

**(a)** DR



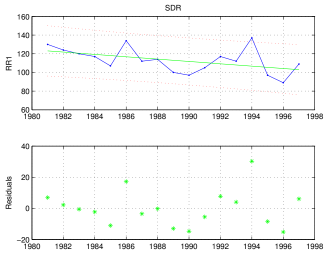

**(b)** SO



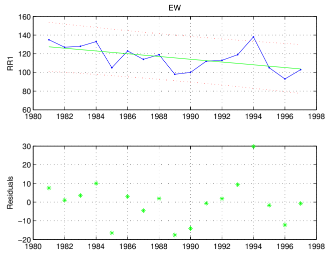

**(c)** PL



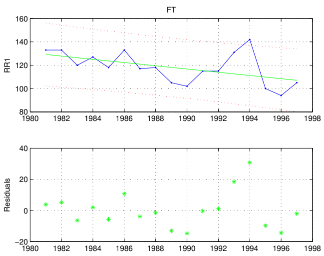

**(d)** PB



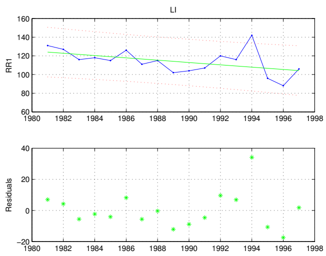

**(e)** SDR



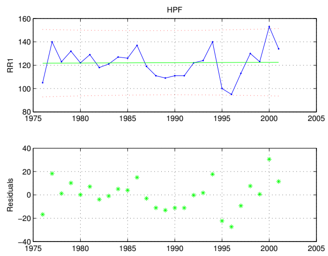

**(f)** EW



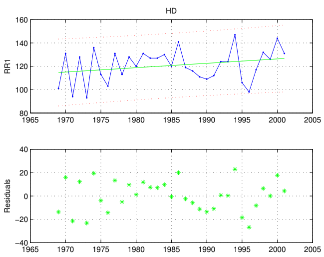

**(g)** FT



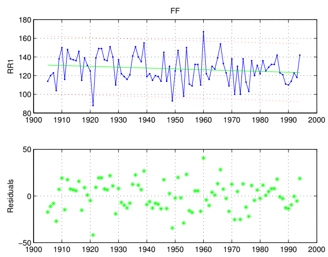

**(h)** LI




**(i)** HPF




**(j)** HD




**(k)** FF

**Figure 3.9** Trends of number of wetdays (RR1) at daily data stations showed upward annual trends in SDII throughout the data periods (Figure 3.10). All the cases with significant trends exhibited increasing trend of annual SDII.

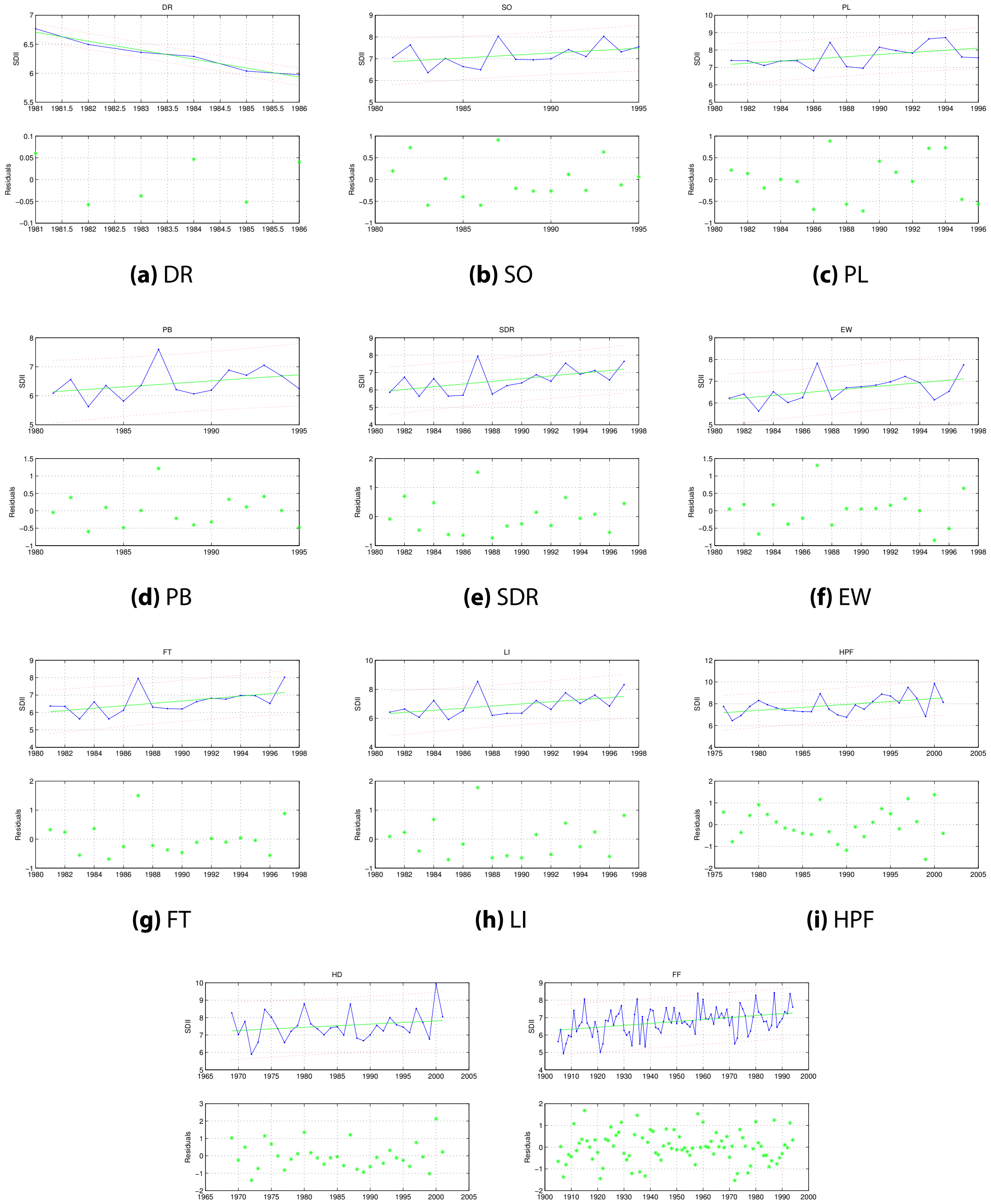
**Number of Days with Precipitation Amount ≥ 10 mm (R10mm)** Annual trends of number of wet days with precipitation amount greater than 10 mm (R10mm) from the studied stations are at variance. Only Falmer Farm Station shows a statistically significant upwards trend for the 1971–1996 period (M-K, $p 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

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

### 3.4.5 Event Precipitation

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

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




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

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

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

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

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

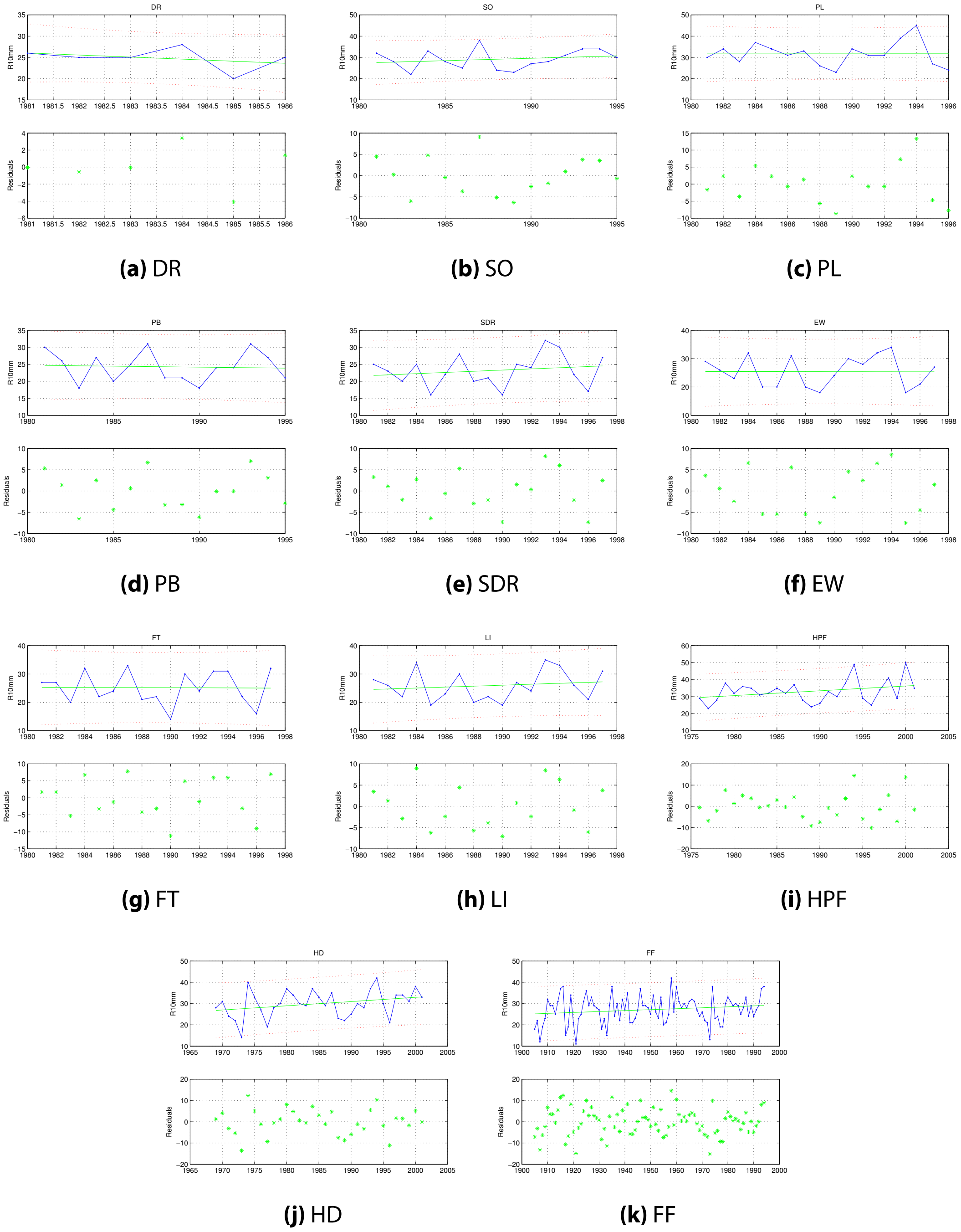
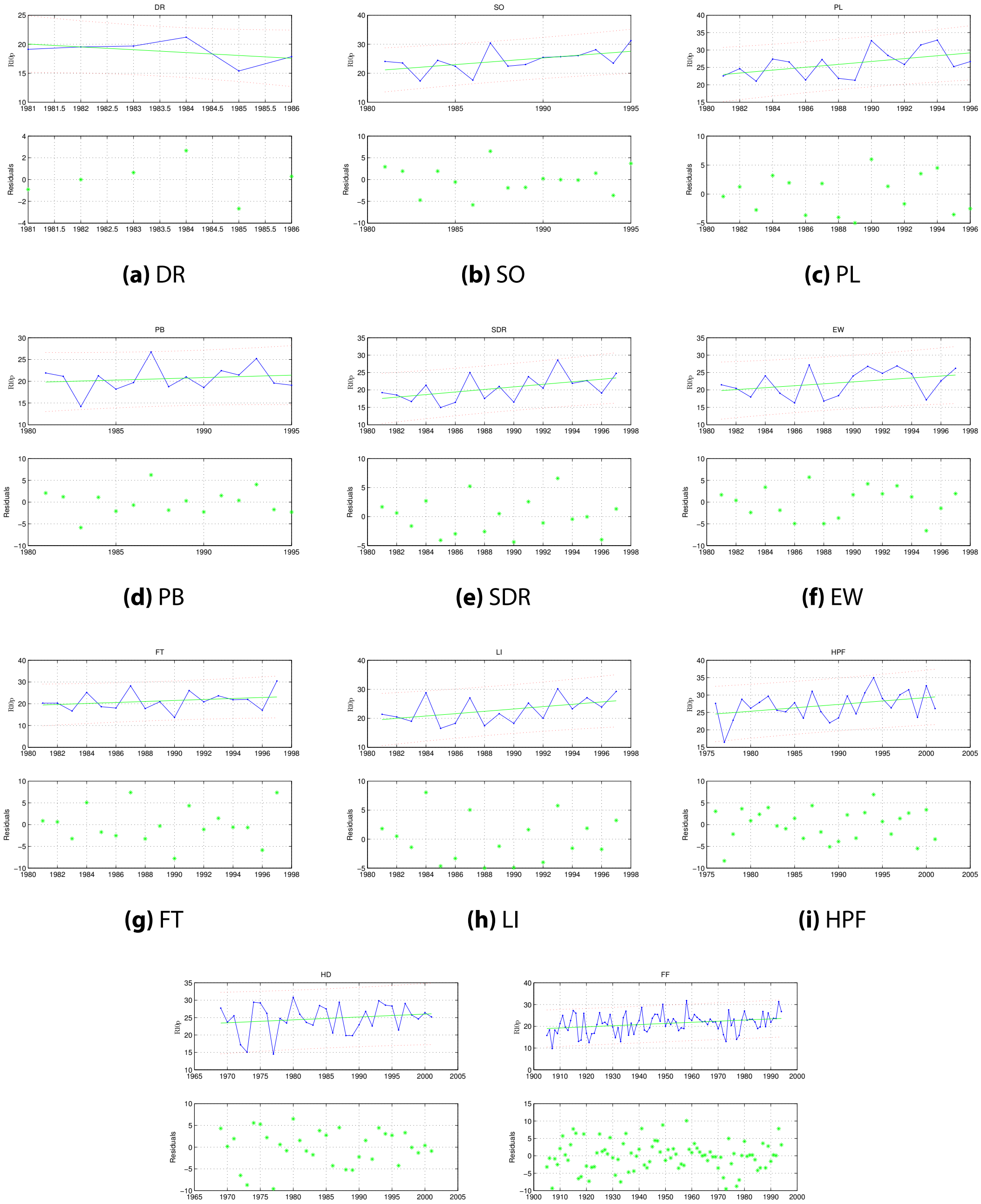



**Figure 3.11** Annual number of wet days with rainfall amount ≥ 10 mm at daily data stations



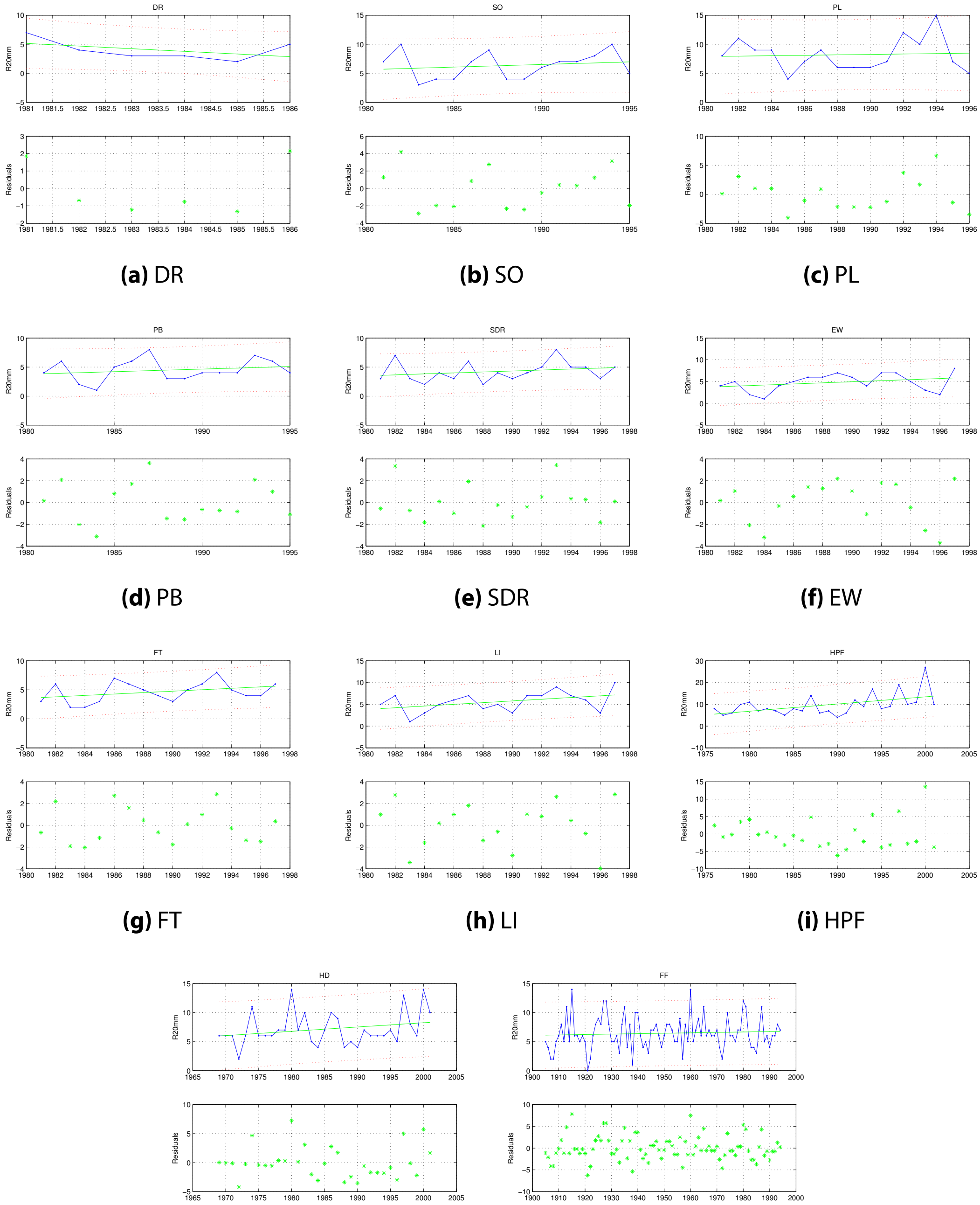

(a) DR (b) SO (c) PL

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

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

(j) HD (k) FF

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



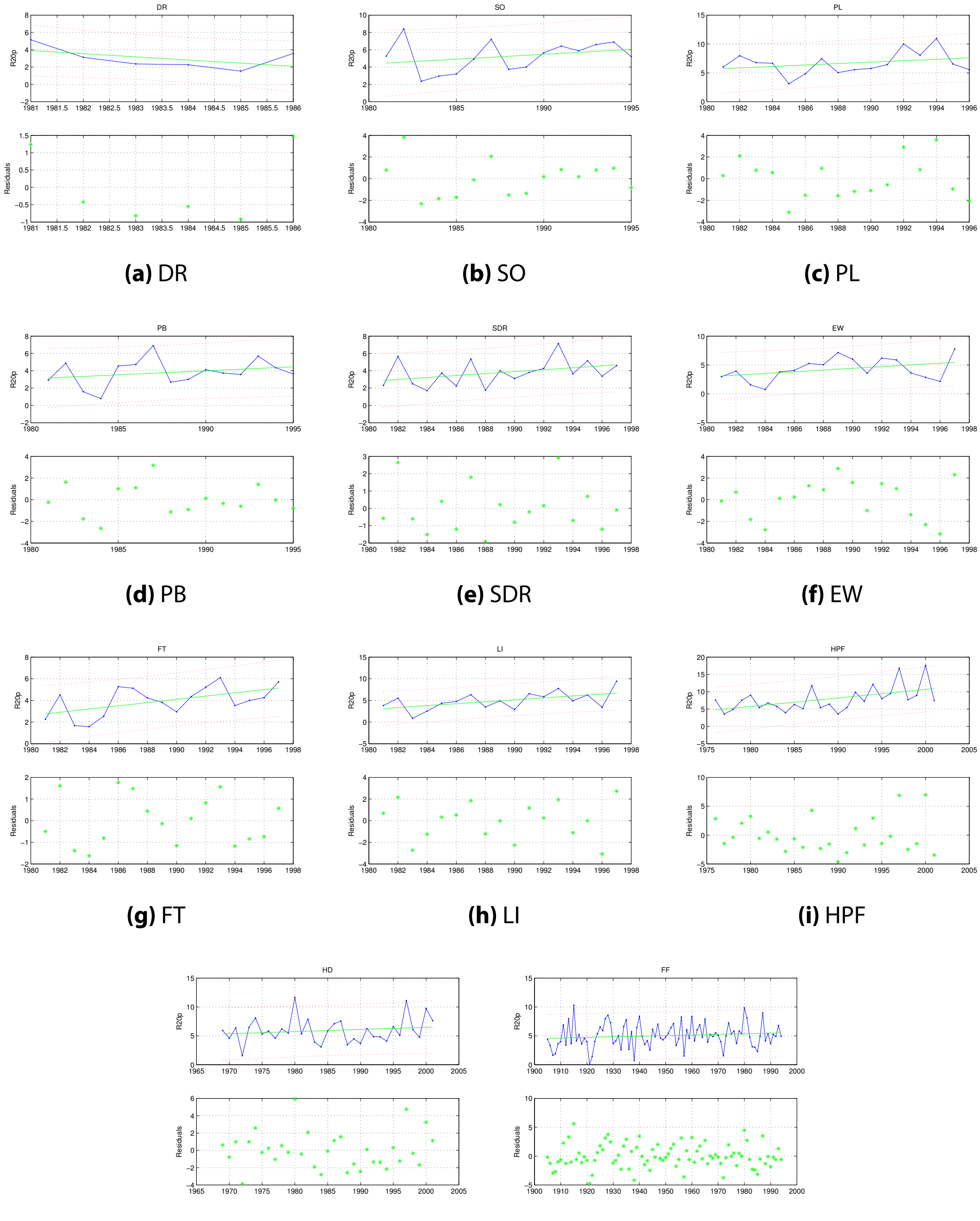

**(a)** DR **(b)** SO **(c)** PL

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

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

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

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




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

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

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

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

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

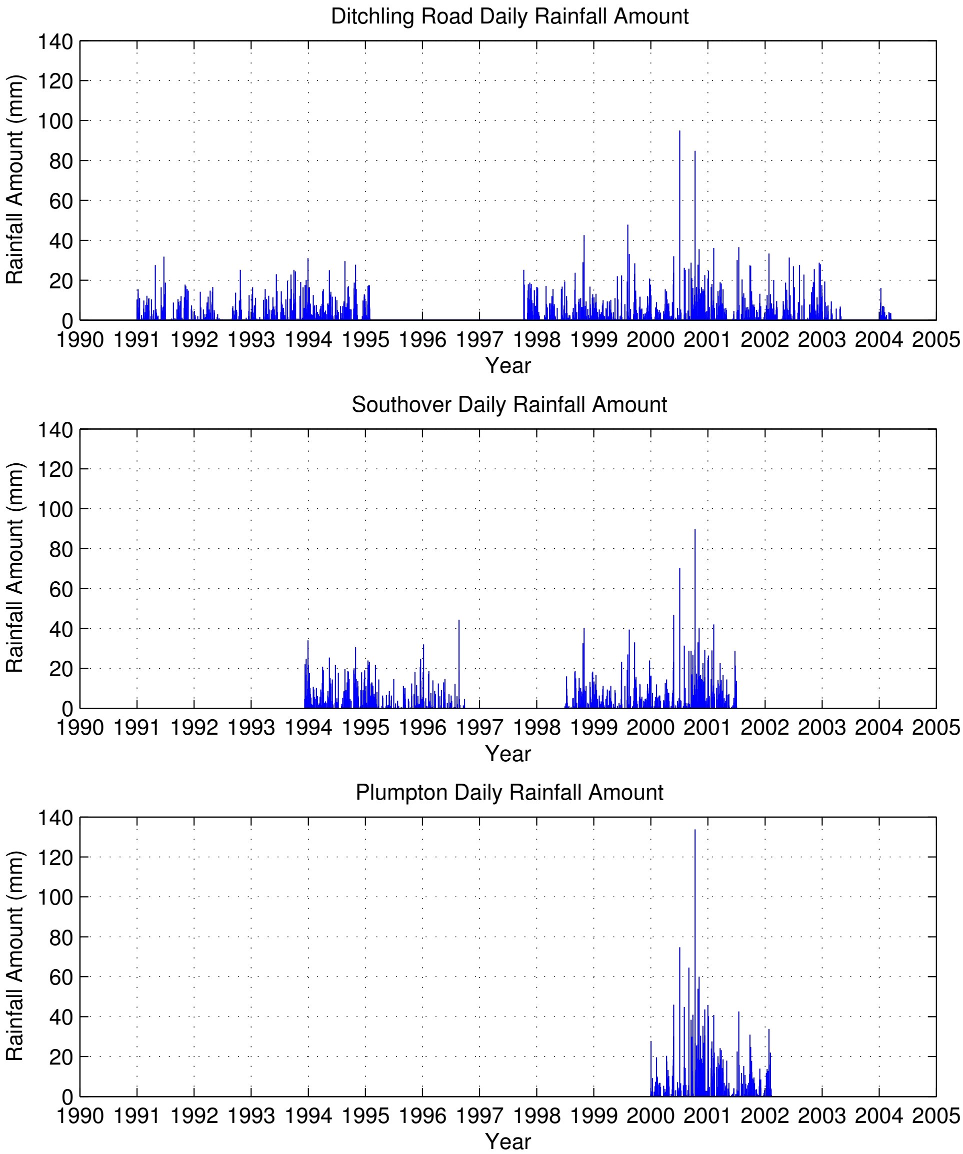



**Figure 3.15** Observed daily rainfall amount

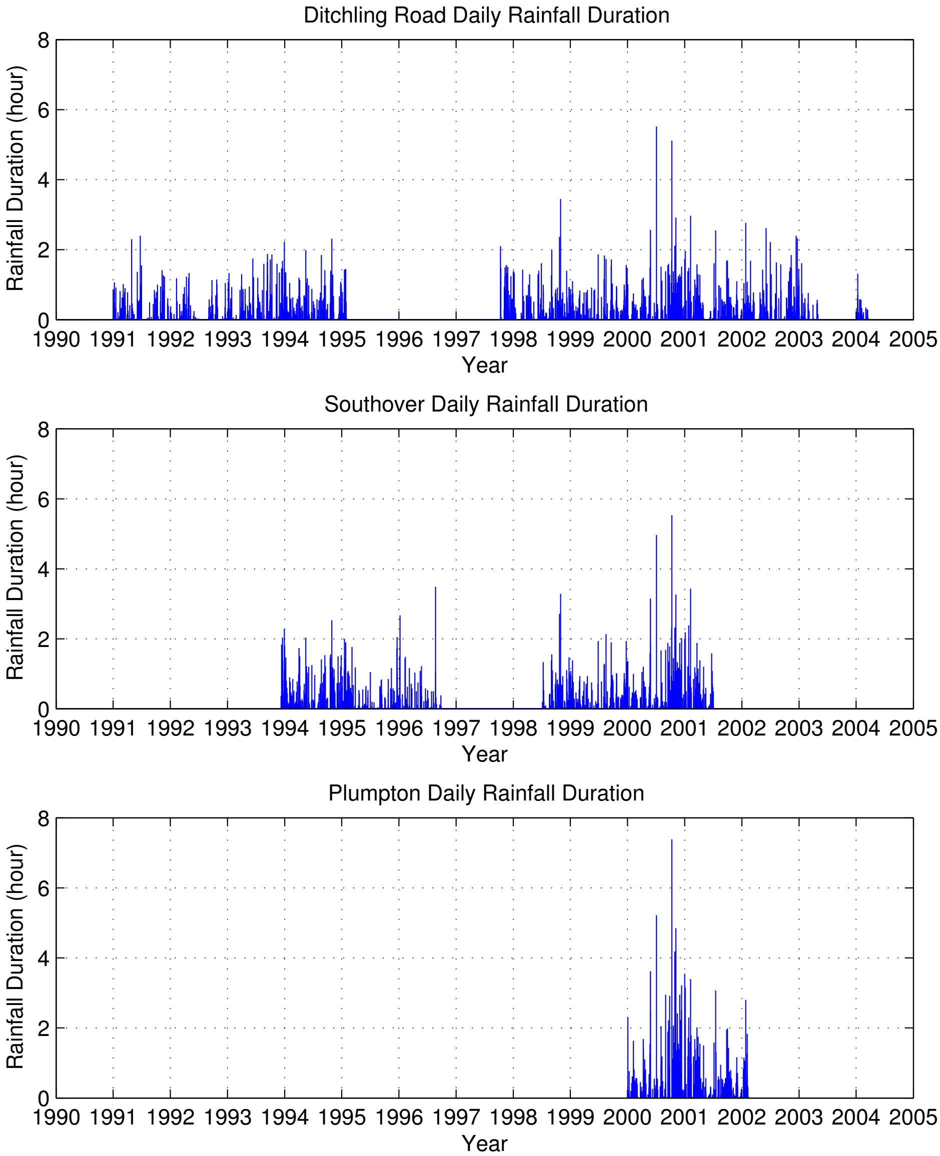



**Figure 3.16** Observed daily rainfall duration

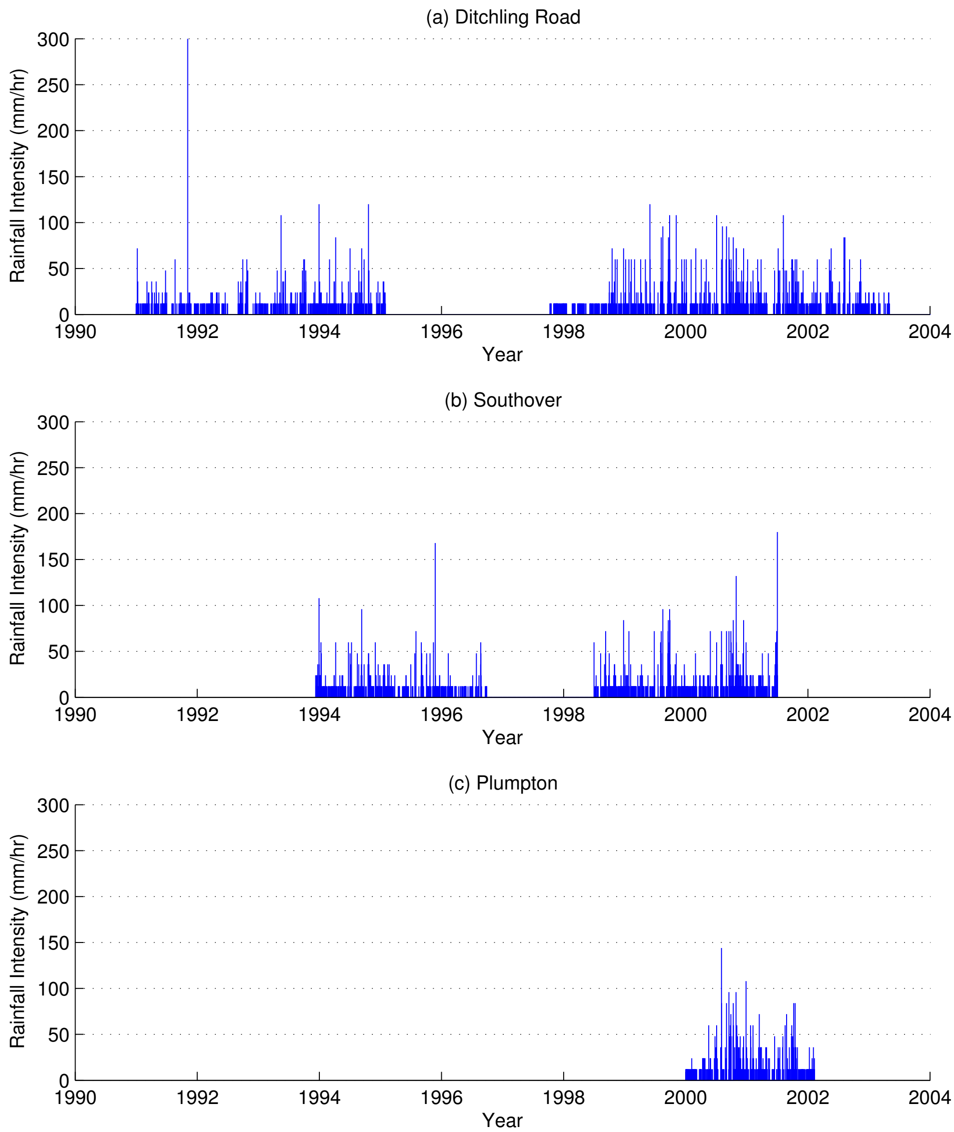



**Figure 3.17** Observed daily 1-min peak rainfall intensity.

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

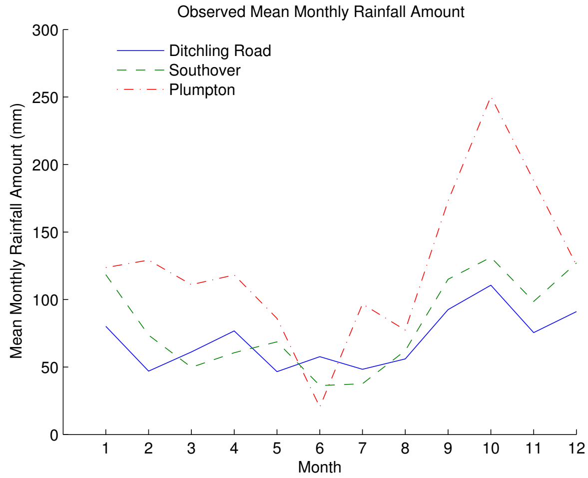



**Figure 3.18** Observed mean monthly rainfall amount

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

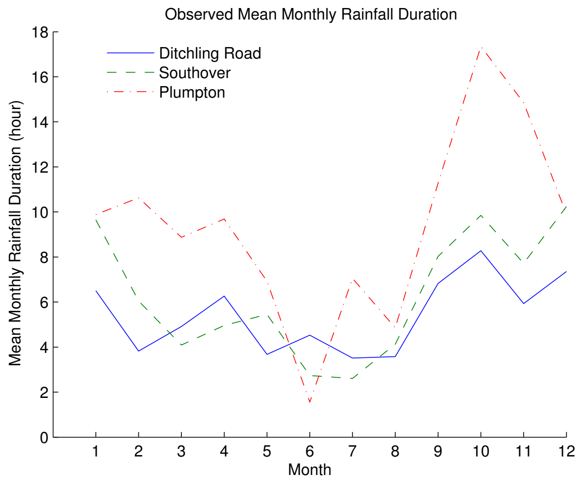



**Figure 3.19** Mean monthly rainfall duration

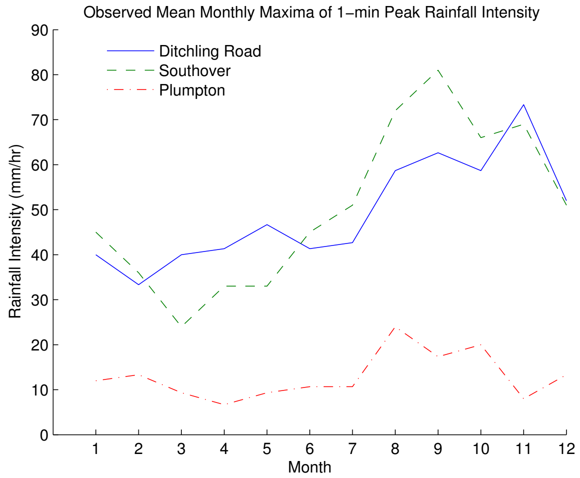



**Figure 3.20** Mean monthly maxima of 1-min peak rainfall intensity

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

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

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

### 3.4.6 Discussion

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

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

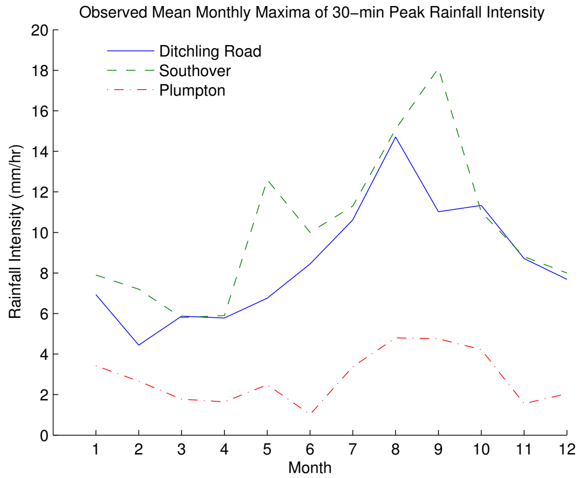



**Figure 3.21** Mean monthly maxima of 30-min peak rainfall intensity

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

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

Tipping-bucket event data evidently gave greater detailed information about rainfall intensity than the other two data types used here. Tipping-bucket event data provide sufficient information about rainfall features for erosion modelling such as duration and peak intensity of the rainfall event. The rainfall parameters for soil erosion model simulation conducted in this research are based on the tipping-bucket data shown in Table 3.2. However, these kind of data may not be suitable for trend studies. This is partly due to the fact that they are not easily accessible and not normally stored long-term.

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

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

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

Knowing the rainfall intensity trend is important for soil erosion estimation for the future. However, detecting the rainfall intensity trend is very problematic considering the variability of available rainfall data scales. Different temporal scales and spatial scales can alter the trajectory of the rainfall intensity trend greatly. Also, rainfall data coarser than a daily scale can not give any useful rainfall intensity information for soil erosion estimation as rainfall intensity patterns within a day can not be determined.

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

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

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

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

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

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

### 3.4.7 Conclusion

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

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

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

This chapter has tried to answer the following research questions:

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

In this chapter, it has been shown that:

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

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

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

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

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