PART II

Rainfall Intensity and Erosion: Model Descriptions and Responses

Chapter 4

IMPLICATION OF IMPROVED CLIGEN

4.1 Introduction

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

This chapter aims to investigate effects of the changes of CLIGEN (from version 4.2 to version 5.2) on WEPP and CLIGEN simulations. In addition, WEPP is calibrated here before being used for the subsequent simulation of this research.

4.2 Data Preparation and Method for Model Simulation

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

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

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

Next, continuous daily climate data for 30 years were generated with CLIGEN version 4.1[2] (old) and version 5.2 (new) using these two input files. As a result, four

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

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

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

datasets of simulated climate data were generated (Table 4.1). These climate data were compared in terms of rainfall amount, duration and peak intensity.

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

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

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

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

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

4.3 Impact on Rainfall Data Generation

4.3.1 Rainfall Amount

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

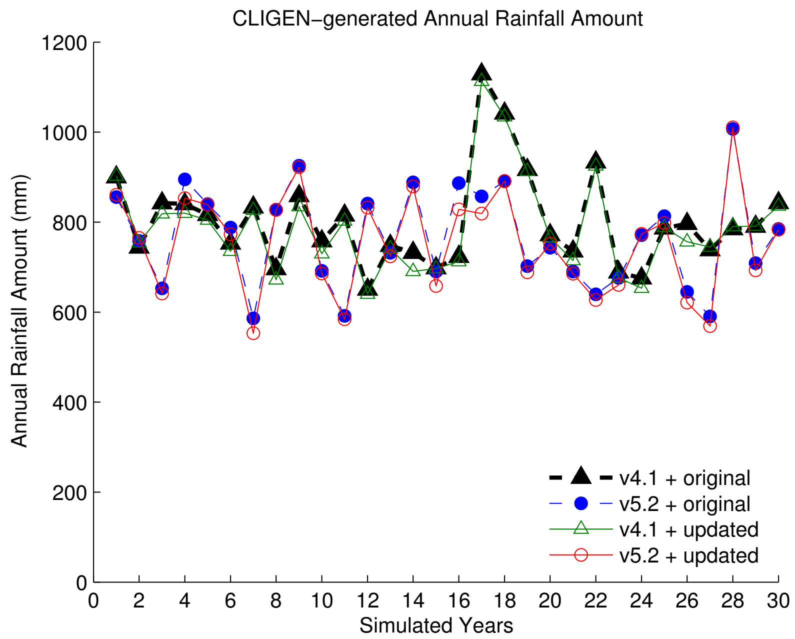


Figure 4.1 Simulated annual rainfall amount using two versions of CLIGEN with original and updated input files.

4.3.2 Rainfall Duration

Simulated annual rainfall durations using two versions of CLIGEN exhibited noticeable differences. Old version of CLIGEN generated identical annual rainfall durations even though two different input files were used (Figure 4.2). New CLIGEN generated markedly different durations when two CLIGEN input files were used (Figure 4.2) (K-S test, $p < 0.05$). New CLIGEN with updated input file generated greatly increased rainfall durations, almost 2.5 times longer on average than with original input file. The rainfall duration was over 1.5 times longer on average in comparison to the rainfall duration generated by old CLIGEN. New CLIGEN with original inputs generated the shortest annual rainfall durations among the four series.

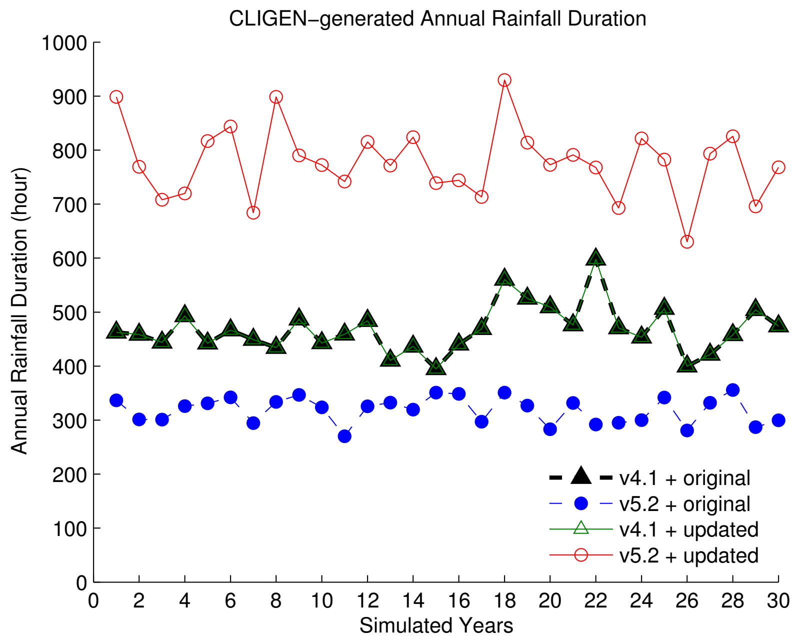


Figure 4.2 Simulated annual rainfall duration using two versions of CLIGEN with original and updated input files.

4.3.3 Monthly Maxima of Daily Peak Rainfall Intensity

Monthly maxima of daily peak rainfall intensity series generated by CLIGEN were compared in order to examine effects of extreme intensity events. The results are shown in Figure 4.3. Kolmogorov-Smirnov tests indicate that old CLIGEN was not sensitive to the changes of input files (See Figure 4.3(a) and 4.3(c)) (i.e. to the changes of MEAN P and MX .5P) ($p < 0.05$). In contrast, using original and updated input files with new CLIGEN resulted in two significantly (K-S test, $p < 0.05$) different distributions of monthly maxima of daily peak rainfall intensity (See Figure 4.3(b) and 4.3(d)). New CLIGEN generated fewer high-peaked rainfall intensity events than the old version (Figure 4.3(a)(c) and 4.3(b)(d)). There were, for example, only nine monthly maxima of daily peak intensity over 100 mm/hr during 30 years of the simulation period when new CLIGEN and updated input file were used (Figure 4.3(d)). The magnitude of the monthly maxima of the daily peak intensity seems to be in a similar range for all four cases although the frequency of such high values may vary depending on versions of CLIGEN and input files.

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

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

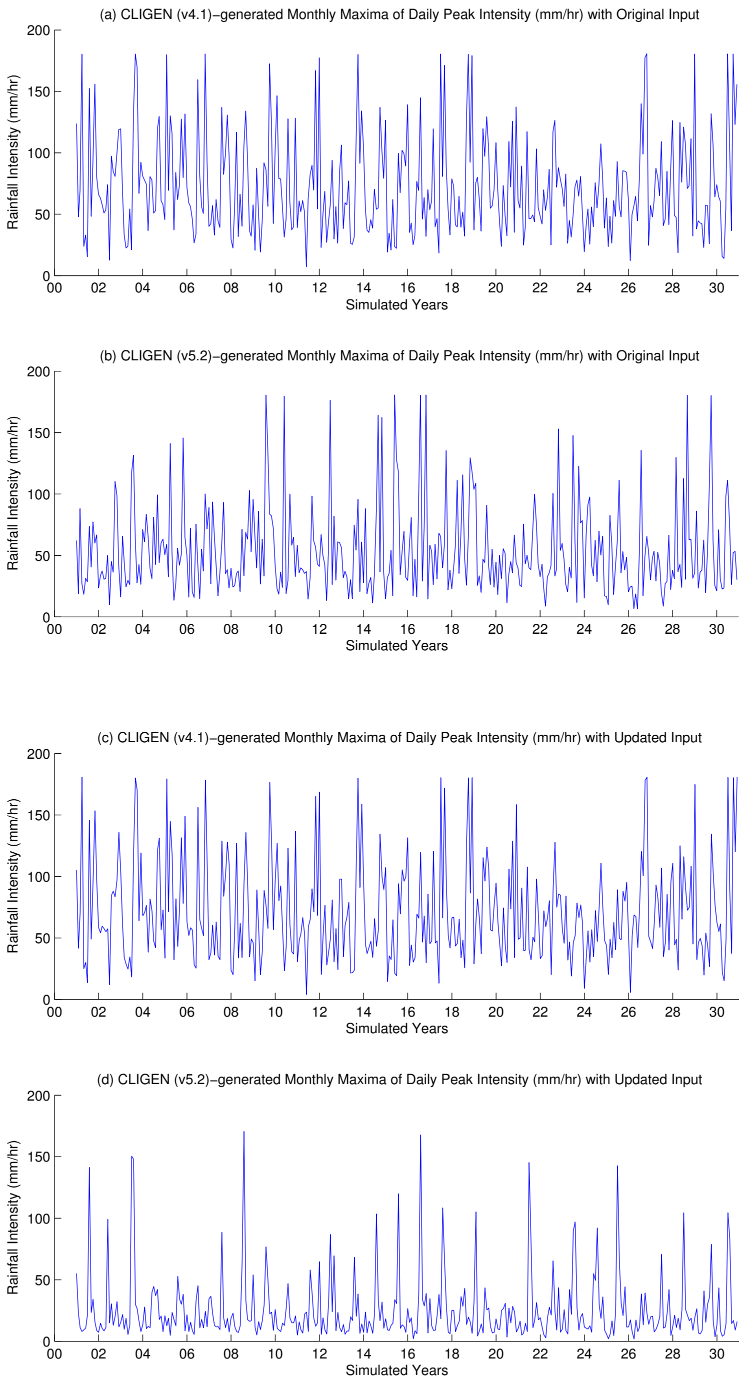


Figure 4.3 Simulated monthly maxima of daily peak rainfall intensity using two versions of CLIGEN with original and updated input files. (a) CLIGEN v4.1 with original input file; (b) CLIGEN v5.2 with original input file; (c) CLIGEN v4.1 with updated input file; (d) CLIGEN v5.2 with updated input file.

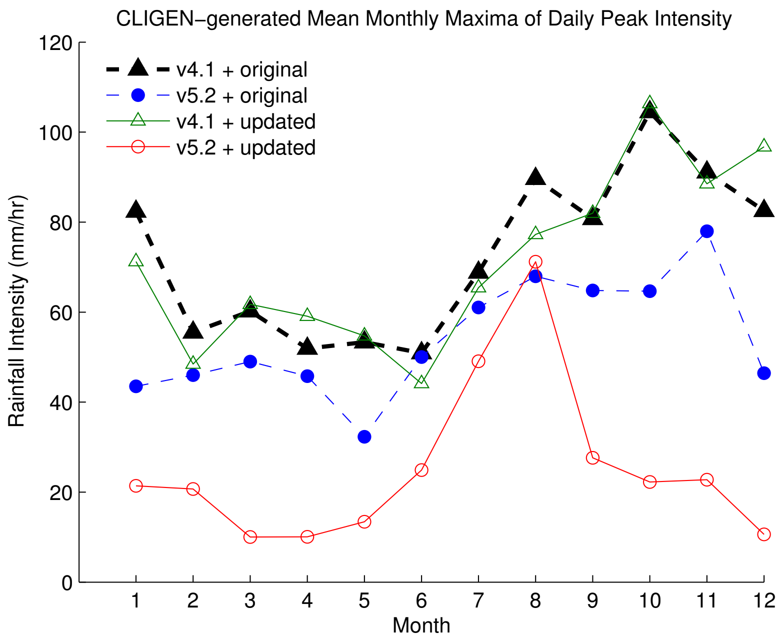


Figure 4.4 CLIGEN-generated mean monthly maxima of daily peak intensity using two versions of CLIGEN with original and updated input files

4.4 Impact on Runoff and Soil Loss Estimation by WEPP

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

Using only relative representations (% change) of model outputs might seem more meaningful than using absolute values (t/ha) together with % changes in this research

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

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

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

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

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

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

Moreover, it is paramount to test and calibrate a model before using it in the subsequent investigation of this research. With model calibrations, high correlations can be expected (Jetten *et al.*, 1999; Favis-Mortlock, 1998*a*). When a erosion model is used for soil loss estimations, it is important to note that the relationship of model inputs and outputs is non-linear. For example, say, we ran a erosion model with $InputA$ and got $OutputB$. Then, in order to find possible effects of changes in inputs, we may change

$InputA$ to $InputA'$. When the model was run with $InputA'$, the responding model output should be $OutputB'$ if the model has a linear relationship between inputs and outputs. However, because of the non-linear relationship, the responding output may be rather unknown $OutputB''$. This means that, unless model inputs and outputs are identified and the model is calibrated against known output values, it may be difficult to measure the extent of changes in model predictions. This is because we may not know where unknown $OutputB''$ has arrived from.

WEPP simulated annual runoff and soil loss rates using four CLIGEN-generated weather series are shown in Figure 4.5 and Figure 4.6, respectively.

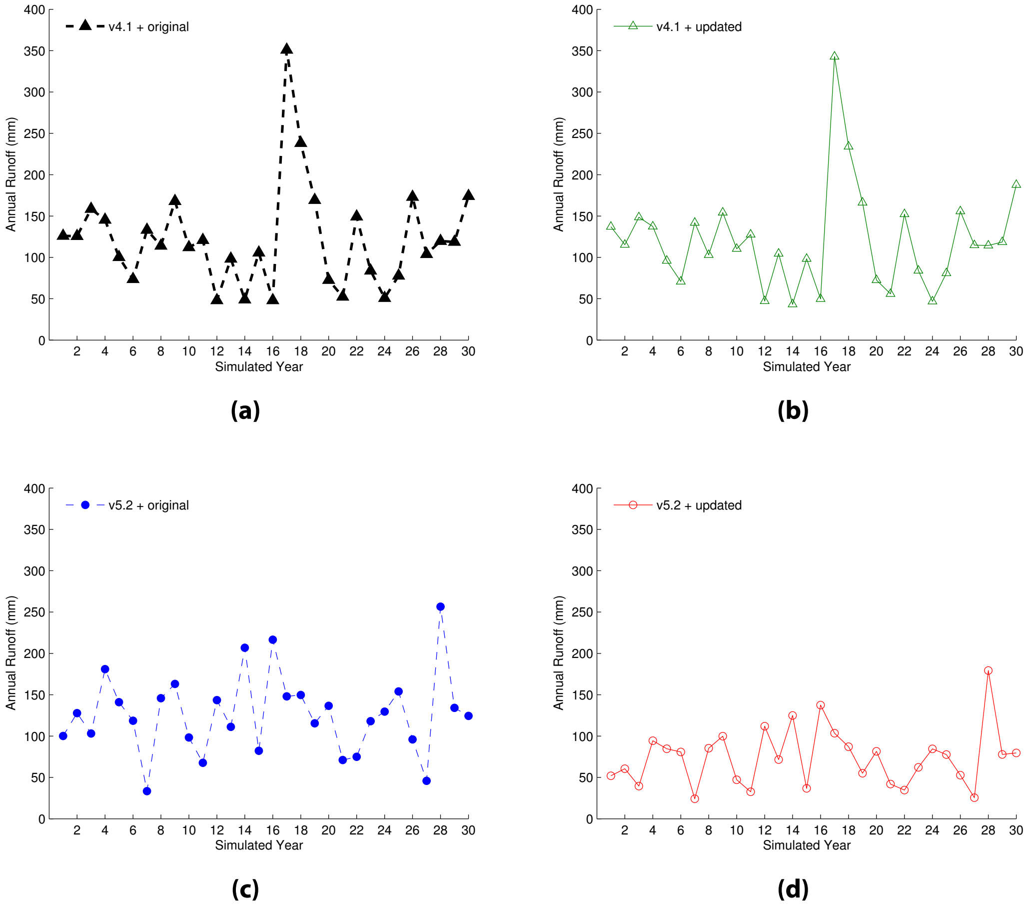


Figure 4.5 Simulated annual runoff for Ditchling Road simulated with (a) old CLIGEN with original input file; (b) old CLIGEN with updated input file; (c) new CLIGEN with original input file; (d) new CLIGEN with updated input file.

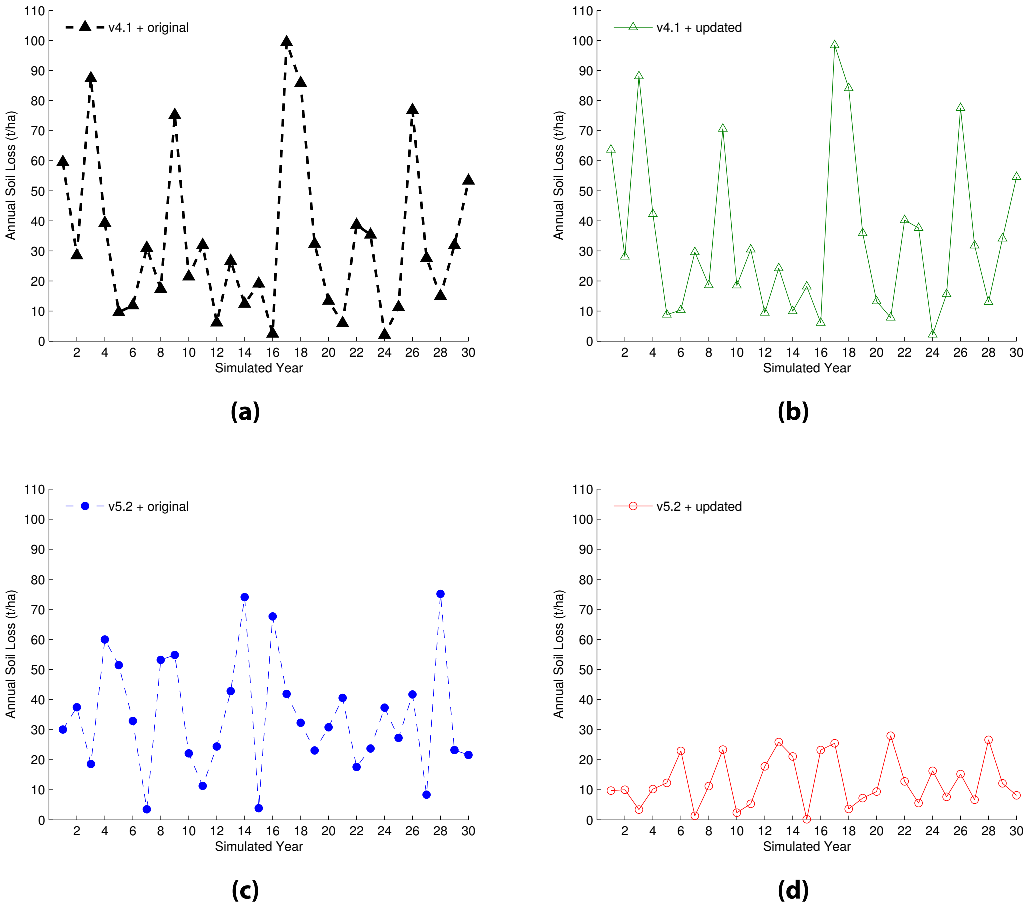


Figure 4.6 Simulated annual soil loss for Ditchling Road simulated with (a) old CLIGEN with original input file; (b) old CLIGEN with updated input file; (c) new CLIGEN with original input file; (d) new CLIGEN with updated input file.

Annual runoff and soil loss rates were not significantly affected by the use of climate datasets that have been generated by two input files with old CLIGEN. Annual runoff (Figure 4.5a and Figure 4.5b) and annual soil loss rates (Figure 4.6a and Figure 4.6b) were almost identical between the two configurations (old CLIGEN with original and updated input files). Mean annual runoff and soil loss rates estimated using climate data generated by old CLIGEN with updated input file were slightly decreased 1.4% and increased 1.5% respectively in comparison to the estimation by the use of old CLIGEN with original input file (Table 4.6).

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

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

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

WEPP with climate data generated by new CLIGEN with original input file estimated the similar average annual runoff and soil loss rates from those simulated with old CLIGEN with original input file with 3.6% and 2.4% increases, respectively (Table 4.6). However, annual runoff and soil loss rates estimated by the use of climate data generated with new CLIGEN were significantly different from annual runoff and soil loss rates estimated using climate data from old CLIGEN (Figure 4.5 and 4.6).

WEPP estimated considerably decreased runoff and soil loss rates when climate data from new CLIGEN with updated input file were used in comparison to the other three configurations (Figure 4.5d and Figure 4.6d). In comparison to mean runoff and soil loss rates estimated by the use of old CLIGEN with original input file, mean annual runoff and soil loss rates decreased about 40% and about 62% respectively when climate data from new CLIGEN with updated input file were used for WEPP simulations (Table 4.6).

4.5 Discussion

4.5.1 Impact on Rainfall Data Generation

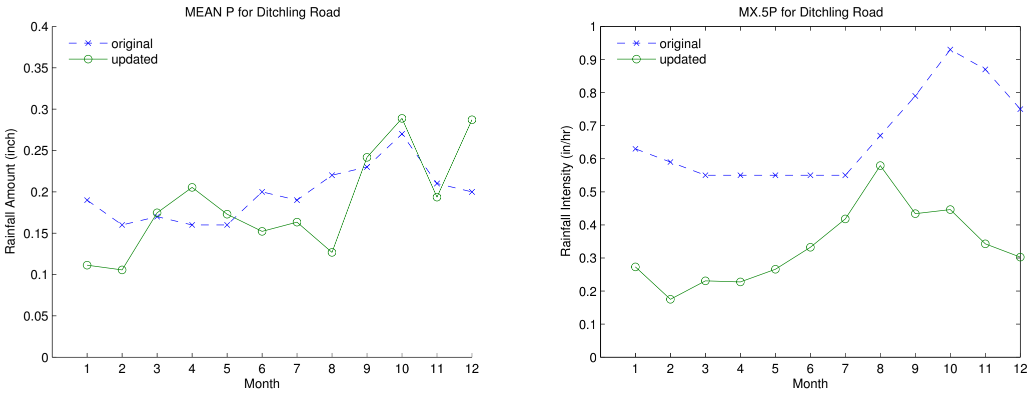
Yu (2000) suggests that CLIGEN became sensitive to the changes in rainfall intensity parameters after the corrections. The investigation conducted here confirms this improvement. Rainfall duration generated by new CLIGEN (v5.2) showed a clear evidence of this improvement (Figure 4.2).

Updated CLIGEN input file that includes lower MX .5P values than original input file resulted in longer rainfall durations as shown in Figure 4.2. This was expected because of the lower MX .5P values and the similar MEAN P values in updated input file (Figure 4.7). With rainfall amount almost unchanged—only slightly changed, but statistically the same ($p < 0.05$), rainfall duration has to be increased to satisfy low intensity parameter (Figure 4.2). This, in turn, decreases generated rainfall intensity (Figure 4.4).

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

New CLIGEN with the updated input file simulated a peak monthly intensity in August that can also be seen in input file (Figure 4.4 and Figure 4.7b). This means that new CLIGEN generates monthly rainfall intensity that are similar to MX .5P values which are calculated from observed weather data.

Old CLIGEN generated the similar monthly rainfall intensity for both input files. This implies that old CLIGEN does not recognize the intensity differences introduced by the different MX .5P parameters in the original input file.



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

Figure 4.7 Mean daily precipitation depth (inch) and mean maximum daily 30-minute rainfall intensity (in/hr) for each month. Note that the units are in inches, not in millimetres, as CLIGEN requires these values in inches.

4.5.2 Impact on Runoff and Soil Loss Estimation

Runoff and soil erosion estimated by WEPP showed the similar result to that from the analysis of climate data generated by CLIGEN. This result may imply that WEPP is sensitive to the changes of climate data which have been used for the simulation.

The two identical climate datasets generated by old CLIGEN with two input files did not affect WEPP estimated annual runoff (Figures 4.5a and 4.5b) and soil erosion rates (Figures 4.6a and 4.6b). There were slight differences between two settings in terms of average annual runoff and soil loss rates (Table 4.6). The differences were however unrealistic as average annual soil loss rate was increased even though average annual runoff was decreased. This suggests that WEPP may have some issues in processing runoff and soil loss rate.

The use of two climate date from the new CLIGEN simulations with two input files resulted in significantly different runoff and soil loss rates between two settings of WEPP simulations. WEPP simulated considerably lower annual runoff and soil loss rates when climate data generated by new CLIGEN with updated input file were used than when climate data generated by new CLIGEN with original input file were used. This can be explained by the stretched rainfall duration which have been caused by the decreases in rainfall intensity. Considering that simulated rainfall amounts (MEAN P) were not much different in both input files of CLIGEN, it is evident that low rainfall intensity (MX .5P) is the reason for the low annual runoff and annual soil loss rates estimated by WEPP.

Another interesting finding is that the differences of average annual runoff and soil loss rates between the simulations of WEPP with new CLIGEN and old CLIGEN with original input file were much smaller than with updated input file. This finding may be explained by the differences in two versions of CLIGEN. New CLIGEN, as shown earlier, is much more sensitive to changes in rainfall intensity than old CLIGEN, so that, with CLIGEN input file that has low rainfall intensity, new CLIGEN will simulate climate data with much lower rainfall intensity. In contrast, with CLIGEN input file that has high rainfall intensity, new CLIGEN still simulate climate data with responding rainfall intensity, that is high rainfall intensity. This is clearly shown in Figure 4.4.

Therefore, the implication of the improvement in CLIGEN is relatively small when new CLIGEN is used to simulate climate data for a place where rainfall events with high intensity are dominant. On the other hand, when new CLIGEN is used to generate climate date for a place where rainfall events with low intensity are dominant (e.g. South Downs, UK), effects on simulated climate data are so great that following WEPP estimations will be greatly affected and have much greater implications.

4.6 Conclusion

The improvement of CLIGEN have clear implications on climate data generations and following WEPP estimations of runoff and soil loss rates. Old CLIGEN is not sensitive to changes of rainfall intensity and generate the similar climate data with both CLIGEN input files that have high and low intensity parameters. New CLIGEN is now sensitive to changes in rainfall intensity which is parametrized as MX .5P. The effect of the improvement of CLIGEN is more significant for the regions where low intensity rainfall events are dominant. This is the case for an area like South Downs, UK where this research is based on.

Chapter 5

EFFECT OF TEMPORAL SCALES OF STORM DATA ON EROSION

5.1 Introduction

When modelling soil erosion, finding suitable input data for the simulation is an important but also difficult part of model-based researches. Ideally, input data need to be measured directly from a study site and parametrized for a model simulation. However, this process requires a great effort and time. It is also frequently affected by geographical and financial situations of research. All these reasons affect how rainfall data are made available in different scales either spatially, temporally or both. Thus, we often end up using what is readily available rather than what is originally required by erosion models.

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

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

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

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

5.2 Simulation Data and Methods

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

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

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

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

Two process-based erosion models, WEPP and EUROSEM, were used at the current stage to simulate runoff and soil loss. WEPP originally requires CLIGEN rainfall data which are stochastically generated using the statistical properties of 15-min rainfall data. CLIGEN data and breakpoint data prepared from rainfall data with 1, 5, 15, 30 and 60-min temporal scale were used to look at the effect of different temporal scale. EUROSEM was also used since it has been designed to use breakpoint rainfall data. Therefore, it would be a good comparison to WEPP which has been originally designed to use CLIGEN data although breakpoint data could also be used.

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

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

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

5.3 Effects on Rainfall Intensity Information

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

Table 5.1 Details of two rain storms observed in Plumpton

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

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

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

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

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

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

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

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

5.4 Effects on Simulated Runoff and Soil Loss

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

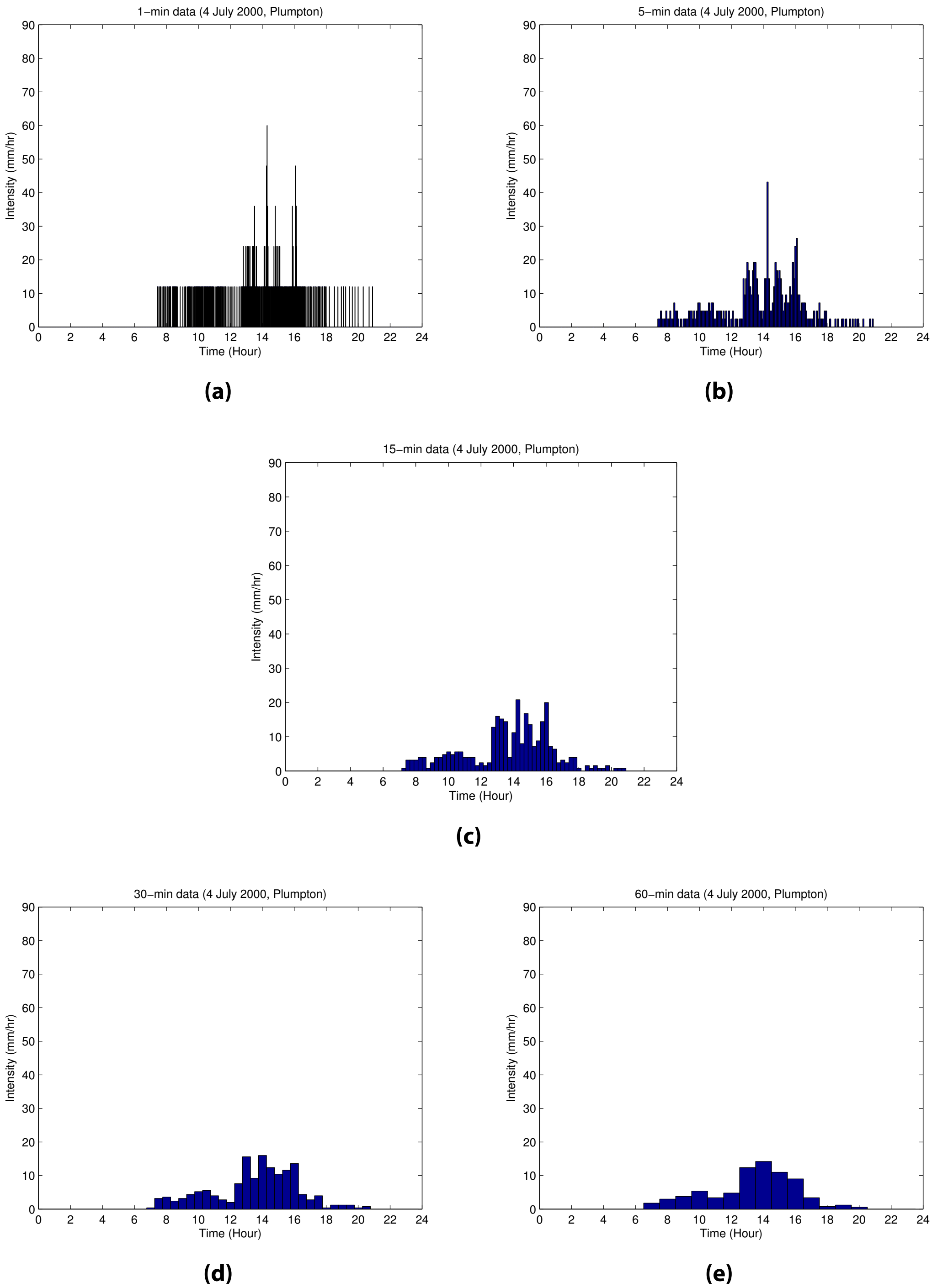


Figure 5.1 Various temporal scales of original breakpoint data for 4 July 2000 storm in Plumpton

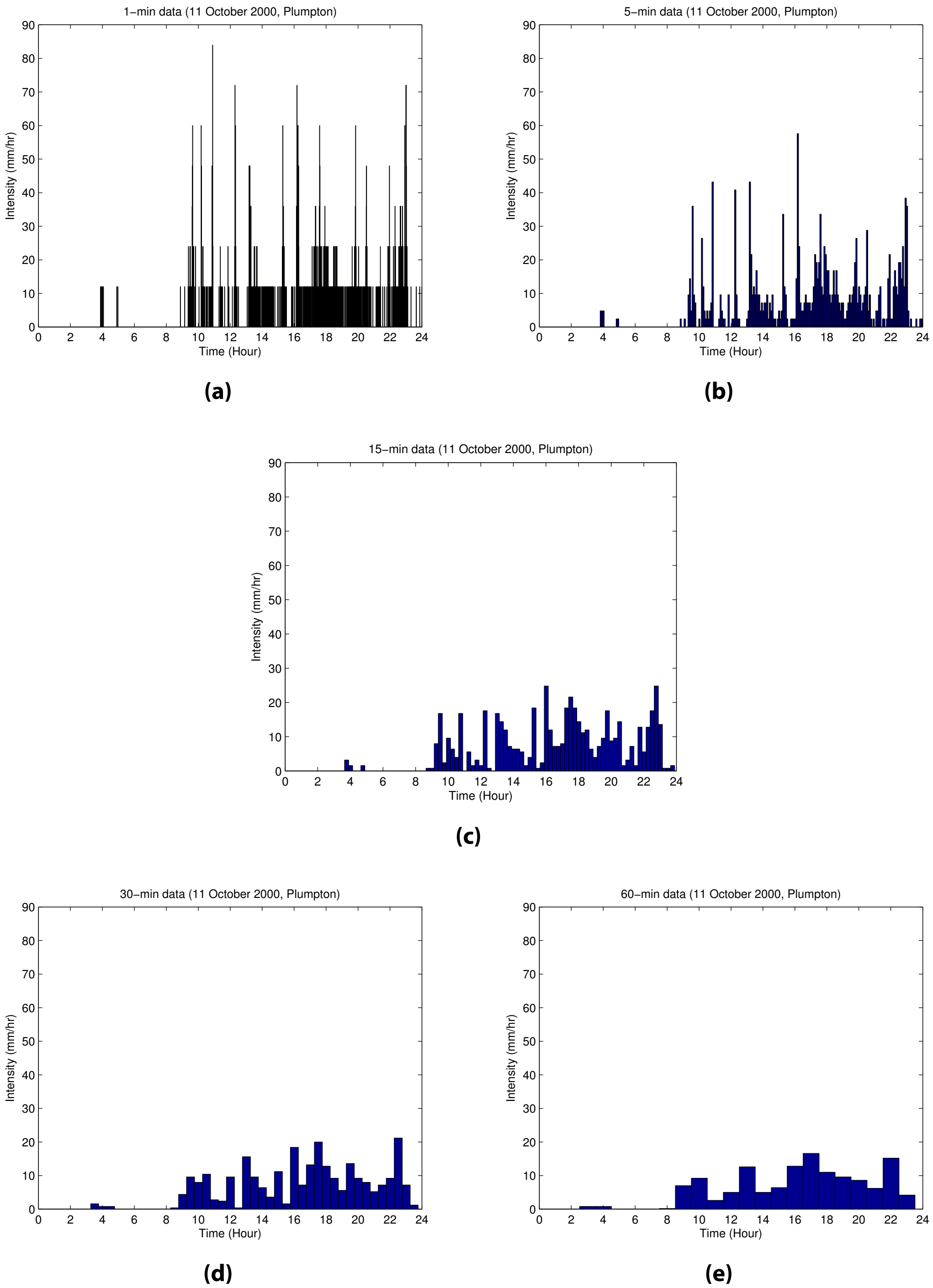


Figure 5.2 Various temporal scales of original breakpoint data for 11 October 2000 storm in Plumpton

5.4.1 Runoff

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

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

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

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

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

When breakpoint data are used, the opposite is observed—the magnitude of the changes are greater for the October event. Also, for the October event, WEPP simulated runoff are greater when simulated with 30 or 60-min breakpoint data than when simulated with 15-min breakpoint data. For the July event, decreases in runoff were observed when lower temporal resolution data were used for the simulation. Despite this disagreement, changing temporal scales of both types of rainfall data influenced runoff generations of WEPP.

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

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

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

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

5.4.2 Soil Loss

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

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

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

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

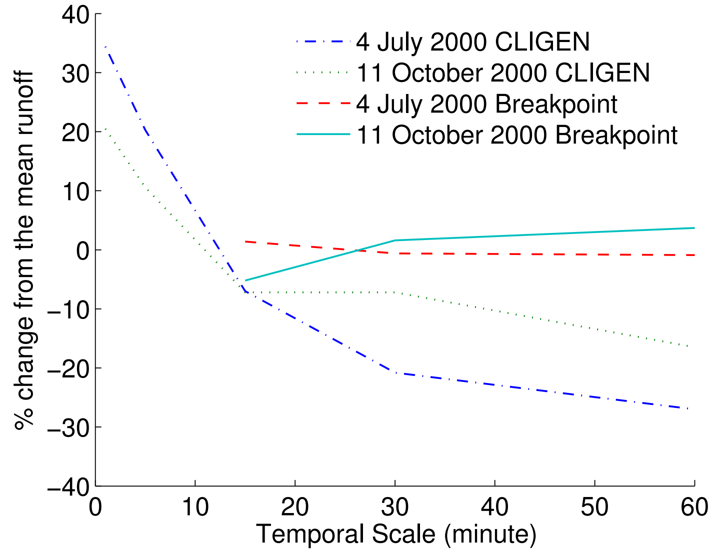
Soil loss rates generated by EUROSEM for rainfall data with the different time scales are shown in Table 5.6 and Figure 5.4(b). The results of soil loss rate simulations using EUROSEM show the reversed effect of the changes in temporal scale on soil loss rates from the effect shown from the WEPP simulation.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

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

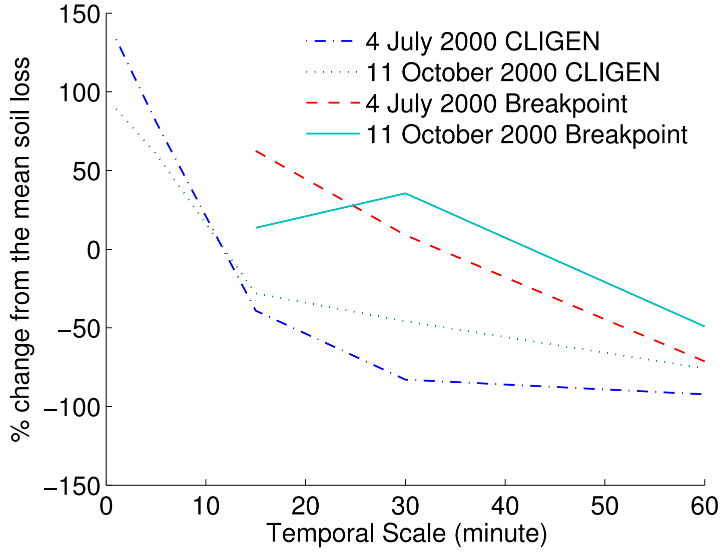
		Temporal Scale (minutes)				
Data type	Event	1	5	15	30	60
CLIGEN	4 Jul 2000	13.0 (+26.2)	10.0 (−2.9)	10.3	10.7 (+3.9)	10.9 (+5.8)
	11 Oct 2000	24.7 (+5.6)	21.5 (−8.1)	23.4	23.8 (+1.7)	25.4 (+8.6)
Breakpoint	4 Jul 2000	–	–	10.0	10.2 (+2.0)	12.0 (+20.0)
	11 Oct 2000	–	–	19.4	21.9 (+12.9)	23.3 (+20.1)

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

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

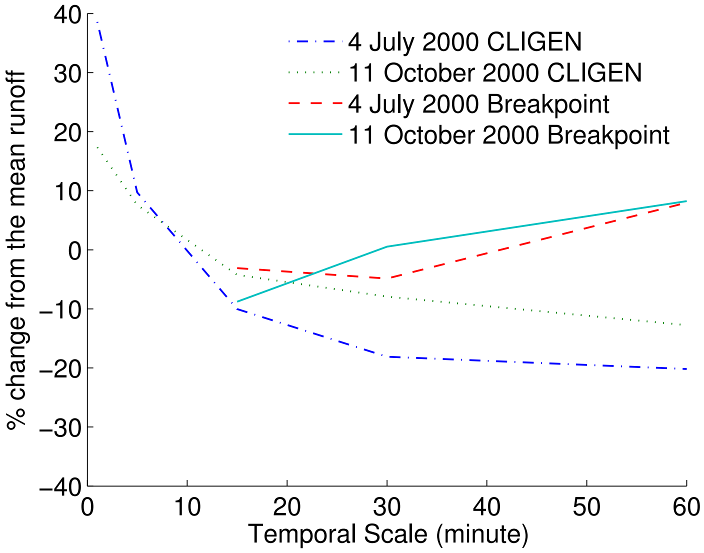


(a) Changes in Runoff

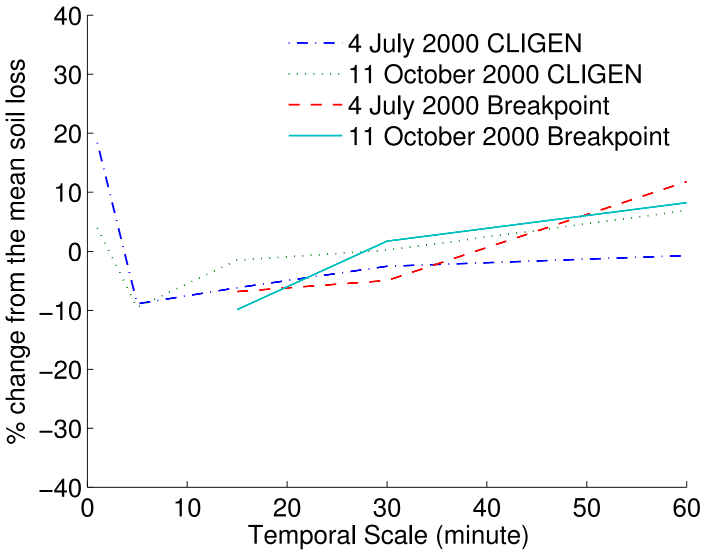


(b) Changes in Soil Loss

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



(a) Changes in Runoff



(b) Changes in Soil Loss

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

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

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

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

5.5 Discussion

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

Breakpoint data that are prepared for both July and October events with 1 and 5-min data could not be used for both models—WEPP and EUROSEM. This is because WEPP limits the number of maximum breakpoint to 50 points per day according to the model document (Flanagan and Nearing, 1995). This means that, for a rainfall event that last for a whole day, 30-min data is the highest resolution we can use for WEPP simulations because there are 48 (24/0.5) intervals per day. This prohibits the use of breakpoint data with temporal resolution higher than 30-min in theory. In practice, any temporal scale could be used as long as the total number of breakpoints does not exceed 50 points. Testing with the most up-to-date WEPP revealed that up to 100 breakpoints may be used without a problem. However, when more than 100 breakpoints were used, WEPP does not recognise the start and end of a rainfall event correctly, and re-aggregates the rainfall with multiple starting times (i.e. 0 minute point). The maximum number of breakpoints should be increased to at least 1440 points or more to enable the use of 1-min data or higher temporal data. EUROSEM have the same limitation which prevent from using more than 100 breakpoints. Also, total 1000 breakpoints for simulations with multiple rainfall gauges. Clearly both models need to increase their dimension of breakpoint data array to meet the need.

Rainfall parameters in the CLIGEN input file are originally calculated from 15-min (breakpoint) data. CLIGEN then uses this statistical information to simulate continuous long-term daily rainfall data which has similar statistical characteristics as the observed data in the form of four unique parameters (rainfall amount, rainfall duration, normalised peak intensity and normalised time to peak). These four parameters then were used by WEPP to disaggregate the daily rainfall data into ten breakpoint data using a double exponential function. This procedure is, however, highly inefficient in retaining original rainfall intensity information, particularly for the event with a long duration and low intensity which is similar to the event occured on 11 October 2000. The rainfall information can be distorted or lost during these data "conversion" processes. An obvious reason why WEPP-CLIGEN use such method seems to be because of the ease of use and data storage for long-term records. This method—statistically summarising historical climate data and maintaining it—is a very efficient way of storing a large amount of rainfall data. One file (i.e. CLIGEN input file) per weather station requires much less space than tipping-bucket data for, say, 10 to 20 years. This however does have a couple of disadvantages:

1. The concept of CLIGEN data is only suitable for convective storms which do not have many intermittent rainfall phases (no-rain periods) during rainfall.

2. For WEPP to disaggregate CLIGEN data realistically using a double exponent function, each storm should have one distinctive high rainfall peak. Such storms are not typical of many parts of the world, and may be seasonally dependant.

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

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

The effect of discarding rainfall intensity information has been clearly shown when both events—i.e. rain storms on 4 July 2000 and 11 October 2000—are aggregated into varying time steps. Distinctive high intensity peaks in 1-min data (Figures 5.1a and 5.2a) was no more visible as intensity was averaged out over the longer timestep data (See Figures 5.1 and 5.2).

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

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

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

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

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

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

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

High temporal resolution data are needed in order to describe the temporal variation of rainfall intensities realistically. High temporal resolution data captures in great detail rainfall intensity patterns including instant high intensity peaks. However, such high resolution data are very rarely available. As Allott *et al.* (2002) pointed out, high-resolution data permit a more detailed assessment of the storm structure and evolution of localised intense storms, but storms are rarely monitored by sub-hourly recording rain gauges. Even if storms are recorded by a sub-hour scale, often the records are converted into hourly or daily for archiving. Thus, a little is ever known about the storm structure and evolution. In many case, therefore, only hourly or daily data are available. Even with hourly (or more generally daily data), the actual rainfall intensity details can not be derived (Figure 5.2) although this information about intensity may be particularly responsible for the runoff and soil loss estimation using erosion models.

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

5.6 Conclusion

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

In this chapter, the following was found:

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

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

Table 5.7 Desirability of different ways of expressing rainfall intensity

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

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

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

Chapter 6

EFFECT OF CONTINUOUS AND DISCONTINUOUS STORM

6.1 Introduction

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

6.2 Simulation Data and Methods

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

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

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

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

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

6.3 Simulation Results

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

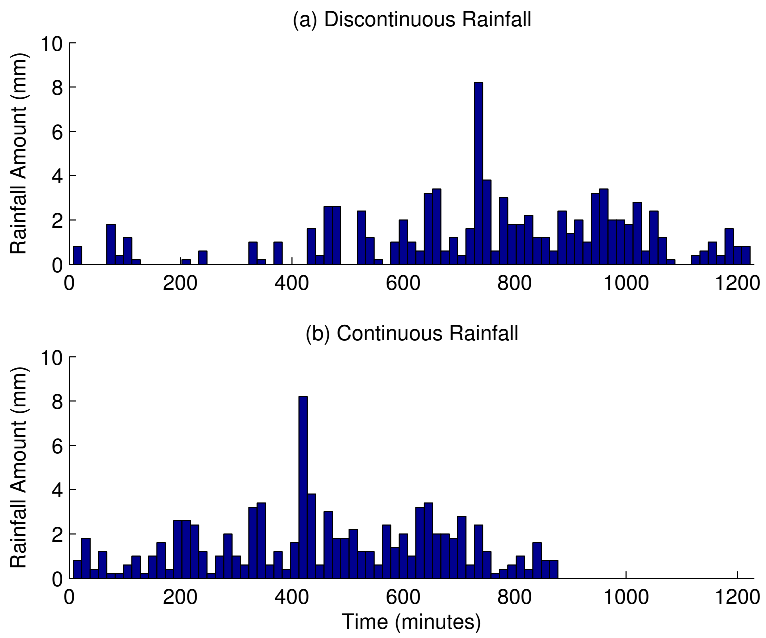
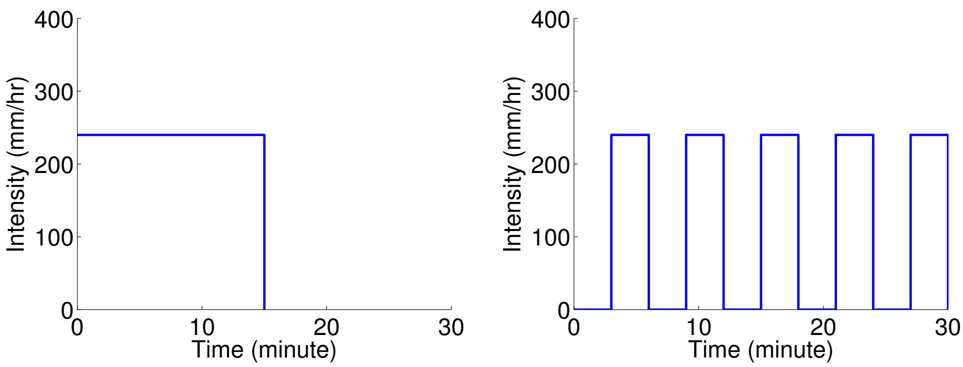


Figure 6.1 15-min rainfall data used for the investigations of effects of continuous and discontinuous rainfall on soil erosion. (a) original 11 October 2000 event ;(b) modified 11 October 2000 event after removing WSPs



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

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

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

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

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

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

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

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

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

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

RillGrow estimated soil loss rates for continuous and discontinuous rainfall are shown in Table 6.3. RillGrow generated less runoff with continuous rainfall than with discontinuous rainfall. With discontinuous rainfall, runoff actually increased 0.2 percent. However, RillGrow estimated more soil loss with continuous rainfall than with discontinuous rainfall. The soil loss rate decreases 1 percent with a discontinuous storm in comparison to the soil loss rate with a continuous storm. Magnitudes of changes for runoff and soil loss are very small compared to WEPP and EUROSEM results.

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

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

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

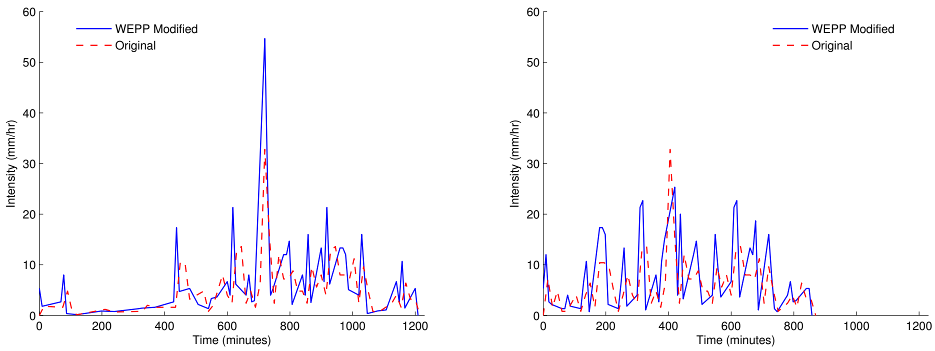
6.4 Discussion

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

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

Using breakpoint data for erosion simulation will prevent the loss of WSP information. However, using breakpoint data for continuous long-term simulation is realistically very difficult since preparing such input for erosion modelling is a very labour intensive and tedious task.

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



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

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

WEPP elongates the peak intensity of discontinuous rainfall from 32.8 mm/hr to 54.7 mm/hr (Figure 6.3). This is about a 66.8% increase in peak intensity. Since the rainfall amount and total duration of discontinuous rainfall were kept almost the same, the average rainfall intensity for the original (4.4 mm/hr) and WEPP modified (4.5 mm/hr) rainfall were also similar.

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

6.5 Conclusion

WSPs (Within-Storm Pauses) affected runoff and soil erosion simulations by WEPP and EUROSEM. However, RillGrow showed almost no changes in runoff and soil erosion simulations. Although it was not evident to conclude whether WSPs have positive or negative effects on runoff and soil erosion estimations, EUROSEM simulated decreased runoff and soil loss rates with rainfall data with WSPs.

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

Chapter 7

EFFECT OF IN-STORM RAINFALL INTENSITY CHANGES ON SOIL EROSION

7.1 Introduction

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

7.2 Simulation Data and Methods

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

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

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

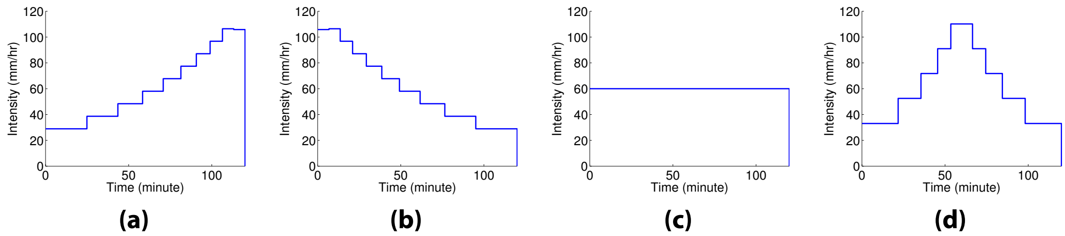


Figure 7.1 Intensity patterns of a convective storm for WEPP and EUROSEM simulations. All the inputs have the same total rainfall amount (120 mm) and duration (2 hour). Note the scales of the axes.

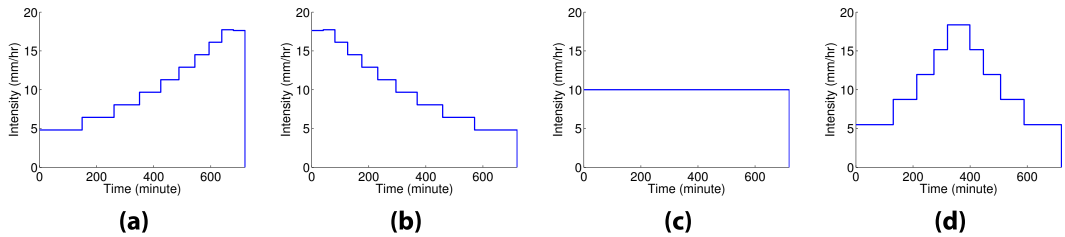


Figure 7.2 Intensity patterns of a stratiform storm for WEPP and EUROSEM simulations. All the inputs have the same total rainfall amount (120 mm) and duration (12 hour). Note the scales of the axes.

7.3 Effects on Runoff and Soil Loss

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

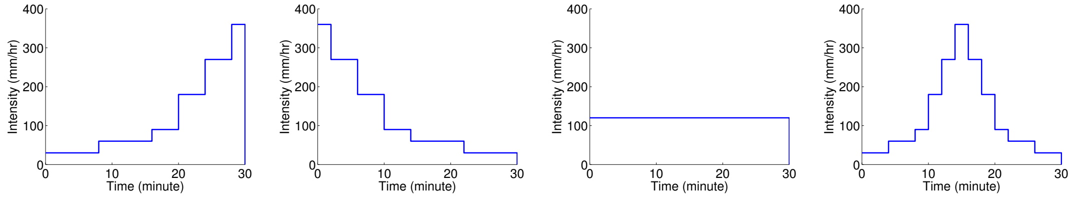


Figure 7.3 Intensity input patterns for RillGrow2 simulations. All the inputs have the same total rainfall amount and duration (i.e. 60 mm rainfall for 30 minutes). Note the scales of the axes.

Table 7.1 WEPP simulation results

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

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

Table 7.2 EUROSEM simulation results

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

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

Table 7.3 RillGrow simulation results

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

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

7.4 Discussion

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

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

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

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

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

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

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

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

Table 7.5 Magnitude of soil loss affected by WSIPs

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

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

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

Because of the fact that their analysis was carried out on the developing version of WEPP and this chapter used the new version of WEPP, their findings may not be compared directly with the result presented in this chapter. However, it is interesting to note that they used relatively high rainfall intensity as a base value for the single storm model input parameter. They used 100 mm/hr intensity while 10 and 60 mm/hr were used for the analysis carried out in this chapter.

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

7.5 Conclusion

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

7.6 Summary of Model Simulation Results

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

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

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

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

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

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

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

7.7 Limitations of Erosion Models

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

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

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

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

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

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

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

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

After each stage, original rainfall intensity information is lost and distorted as this research has shown.

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

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