

# 1 Introduction

## 1.1 Overview

It is necessary to determine whether the rehabilitated landforms of Ranger Uranium Mine, Northern Territory, Australia, will meet their design specifications, specifically, the containment of uranium mill tailings for several hundred years. Computer modelling of geomorphic processes, and particularly of the degradation of the engineered landforms, is a crucial aspect of the assessment program. As a first stage in the development of assessment procedures, the computer model developed by Willgoose et al (1989, 1990, 1991a,b,c,d), which can simulate the evolution of landscapes over time (SIBERIA), is calibrated to existing hydrogeomorphic data. This report presents details of the calibration of the model and predictions made by it of the likely development of engineered landforms of a rehabilitated Ranger uranium mine.

Details of the research strategy and background to the problem of geomorphic modelling of Ranger are given in Riley (in prep). The following is a brief discussion, details are given in Riley (in prep). It is assumed in the following sections that the reader has access to the background report.

Ranger uranium mine is located in the seasonally wet tropics, has an average annual rainfall of 1500 mm, and is an area of low relief and extremely low rates of denudation ( $<20 \text{ mMa}^{-1}$ ). The mine is located in the World Heritage Listed Area of Kakadu National Park, adjacent to Magela Creek, along which are important wetlands and cultural heritage sites.

The rehabilitation of the mine will involve shaping waste rock dumps, consisting of more than 100 million tonnes of waste rock and low grade ore, and containing the mill tailings. The mill tailings may be rehabilitated either above- or below-grade and must be contained in structures with 'structural lives' in excess of 1000 years. Ranger Mines Pty Ltd (RUM) prefers the above-grade option. However, the Environmental Requirements for the mine specify tailings disposal options as follows: 'that by dealing with tailings... the environment will be no less well protected than by transferring the tailings to the mine pits...'. Engineered landforms will be constructed from waste rock—a chlorite rich schist that weathers rapidly to gravels and clay fractions. Geomorphic processes will largely determine the long-term stability of the structures.

Supervisory and regulatory authorities need a means of determining whether designs will perform in accordance with design guidelines. A geomorphic model is needed to assess the long-term stability. The model needs to predict the long-term changes in landforms and the likely water and sediment discharge from the site over time. The research program for developing and testing this model has involved detailed studies of erosion and hydrologic processes on waste rock and natural sites, as well as assessment of risk of dispersal of potential contaminants. Monitoring and simulation were used to collect hydrogeomorphic data for examining the critical processes and providing a data set for calibration of hydrogeomorphic models.

A review of available models suggested that the geomorphic model, SIBERIA, was suitable for the assessment. Hence, it was calibrated on the hydrogeomorphic data and predictions made of landform stability. A series of objectives were set as part of this evaluation.

## 1.2 Objectives

The objective of this project is to assess the long-term erosional stability of engineered landforms at the Ranger uranium mine using the Willgoose Catchment Evolution Model (SIBERIA).

Specific objectives of this project are:

- 1 To calibrate the Willgoose Catchment Evolution model (SIBERIA) using data supplied by the Geomorphology Group at *eriss*.
- 2 To test the erosional stability of the ‘above- and below-grade’ options for engineered landforms as currently proposed by RUM.
- 3 To identify sections of SIBERIA that may need modification and outline the research needed to undertake these modifications.
- 4 To identify geomorphic research needed to further develop SIBERIA for use at RUM.
- 5 To present the model in a form that will enable different design options for the engineering of rehabilitation landforms to be tested, within the constraints of the model.
- 6 To predict particulate discharge in the form of sedigraphs.

The work to achieve these aims is divided into two stages. This report discusses the first stage of the project and addresses objectives 1–4. The second stage report addresses objectives 5 and 6.

## 1.3 SIBERIA – long-term landscape evolution model

SIBERIA is a computer model for studying the erosional development of catchments and their channel networks. A crucial component of this model is that it explicitly incorporates the interaction between the hillslopes and the growing channel or gully network based on physically observable mechanisms. The elevations within the catchment—both hillslope and channel—are simulated by a mass transport continuity equation applied over geologic time. Mass transport processes considered include fluvial sediment transport, such as modelled by the Einstein-Brown equation, and mass movement mechanisms such as creep, rainsplash or landslide. An explicit differentiation between the processes that act on the hillslopes and in the channels is made. The growth of the channel network is governed by a physically based threshold mechanism, where if a function (called the channel initiation function) is greater than some predetermined threshold then channel head advance occurs. The channel initiation function is primarily dependent on the discharge and slope at that point, and the channel initiation threshold is dependent on the resistance of the catchment to channelisation. Channel growth is thus governed by the hillslope form and processes that occur upstream of the channel head, but in a way that that can be independent of channel growth stability arguments (Smith & Bretherton 1972). The elevations on the hillslopes and the growing channel interact through the different transport processes in each regime and the preferred drainage to the channels that results. The interaction of these processes produces the long-term form of the catchment. The preferential erosion in the channels results in the familiar pattern of hills and valleys with hillslope flow being towards the channel network in the bottoms of the valleys.

The model has two main components. The first component is a model of elevation variation; the second component is a model of where the channels are formed in the catchment. The channels develop in response to changes in the elevation, and in turn, the elevations change in response to the channels.

The first component of the model, the variation of elevation within the catchment, is simulated by a mass transport continuity equation applied over geologic time. If more material enters a region than leaves it, then the elevation rises and vice versa. The mass transport processes in SIBERIA include both fluvial sediment transport and a conceptualisation of diffusive mass movement mechanisms such as creep, rainsplash and landslide. The model averages these processes in time so that the elevations (and the channel network) are indicative of the average, with time, of the full range of erosion events; the elevations simulated are average elevations with time. The model explicitly differentiates between the transport processes that act on the hillslope and in the channel.

The model's second component, the channel network, is simulated by an equation that initiates the advance of the channel heads into the surrounding hillslopes. Catchments start with an initial pattern of channelisation, or no channelisation at all, and channel head advance occurs when a channel initiation function, nonlinearly dependent on the local slope and discharge, exceeds a threshold, characteristic of the landscape. Conceptually this threshold can represent overland flow velocity or shear stress, subsurface flow criteria or criteria based on local landsliding at the channel head.

The first component of the model, the governing equation of the elevations in the catchment model, is expressed as:

$$\frac{\partial z}{\partial t} = c_0 + \frac{\nabla \cdot \mathbf{q}_s}{\rho_{sb}} + D \left( \frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} \right) \quad 1.3.1$$

where	$x, y$	horizontal directions
	$z$	elevation
	$t$	time
	$c_0$	tectonic uplift
	$\mathbf{q}_s$	sediment transport per unit width (mass/time)
	$\rho_{sb}$	bulk density of the sediment
	$D$	diffusivity

Variables whose variation in space and time is dependent on the form of the catchment, and thus change as the simulated catchment evolves in time, are highlighted here in bold. All other parameters, though they may vary in space and time, are considered independent of the evolving form of the catchment. The detailed behaviour of these equations will not be discussed in detail here as it has been dealt with adequately elsewhere (Willgoose et al 1991a,b,c,d).

The differential equation for elevation (equation 1.3.1) is a continuity equation in space for sediment transport. It is an average equation that models the average sediment transport over many erosion events to give the average elevations with time. The first term in the elevation equation is the rate of tectonic uplift (positive upwards). This term may be time varying. The third term in the elevation equation represents diffusive mechanisms occurring in certain mass transport processes, such as creep, rainsplash and landsliding (Culling 1963, Dunne 1980, Andrews & Bucknam 1987). The rate of these processes is governed by the diffusivity  $D$ . Both the diffusivity and tectonic uplift may vary over the catchment but are not dependent on the form of the catchment. In principle, it is possible to use more sophisticated diffusive processes in models of hillslope evolution but at this time data do not appear to be available to define them accurately. These enhancements (eg viscous and plastic flow) are typically

spatially variable and dependent on soil depth. At this time SIBERIA does not model the chemical and physical processes associated with weathering and soil formation. Accordingly, it cannot model those processes that depend on soil depth.

The sediment transport process,  $q_s$ , modelled by the second term in equation 1.3.1, can be parameterised in any way that is believed to reflect the processes occurring in the catchment. Willgoose et al (1989) and others (eg Kirkby 1971) suggest that a realistic formulation is of the form

$$q_s = f(Y) G q^{m_1} S^{n_1} \quad 1.3.2$$

where	$q_s$	sediment transport per unit width (mass/time)
	$q$	discharge per unit width
	$S$	slope in the steepest downstream direction
	$f(Y)$	a sediment transport coefficient dependent on the pattern of channelisation, discussed below
	$G$	a function dependent of the runoff process modelled, discussed below
	$m_1, n_1$	sediment transport coefficients

This fluvial sediment transport term is one that has been commonly used by geomorphologists (Kirkby 1971, Smith & Bretherton 1972, Moore & Burch 1986) to represent a transport-limited process. It can be directly related to generally accepted instantaneous sediment transport physics, such as Einstein-Brown, by averaging over the range of flood events. Briefly, when modelling the instantaneous sediment transport rate the appropriate discharge to use is the instantaneous discharge at that time. However, here the equation is used to model the mean sediment transport, so that the appropriate discharge to use is the mean peak discharge derived from a frequency analysis of runoff events (Willgoose et al 1989). This averaging of the sediment transport is carried out in section 4.3. Note that we describe as fluvial erosion any sediment transport processes that result from surface runoff, whether they be on the hillslope, as sheet or rill flow, or in the channels.

The function  $G$  indicates what *proportion of storms* saturate that point and thus generate surface runoff. It is only during those storms when surface runoff is generated that fluvial erosion occurs. The calculation of this parameter is discussed in further detail in Willgoose et al (1991e). Suffice to say that for Hortonian runoff it might be assumed that  $G=1$ . For subsurface saturation generated runoff, smaller storms saturate a smaller proportion of the catchment than do larger storms. Thus for subsurface saturation runoff,  $G$  is less than 1 and largest in those parts of the catchment saturated most frequently.

The slope in the fluvial sediment transport equation is determined directly from the catchment elevations and the direction of steepest downhill drainage. The discharge relationship, dependent on area and slope, can be formulated to reflect the processes that occur in the field. However, it is important to note that if the sediment transport equation is to model the *long term average* sediment transport equation then the discharge per unit width,  $q$ , should be interpreted as the mean annual peak discharge, analogous to the idea of a dominant discharge (Willgoose et al 1989), so that

$$Q = \beta_3 A^{m_3} S^{n_3} \quad 1.3.3$$

where  $Q$  discharge in the channel  
 $\beta_3$  runoff rate constant  
 $S$  slope in the steepest downstream direction  
 $A$  area per unit width  
 $m_3, n_3$  exponents

This relationship is calibrated in section 4.2 of this report. This empirical relationship accounts for runoff routing effects within the catchment and the spatial correlation of rainfall (Leopold et al 1964, Pilgrim 1987).

A crucial feature of this model is its ability to explicitly model the extension of the channel network and to allow for different sediment transport processes in the channels and on the hillslopes. A variable is defined,  $Y$ , that identifies where channels exist ( $Y \approx 1$ ) versus where the catchment is hillslope ( $Y \approx 0$ ). Initially a catchment can either have no channels or it can have a predefined channel network and drainage pattern. The extension of the network occurs when a function, nonlinearly dependent on contributing area slope, called the channel initiation function  $a$ , exceeds a threshold value called the channel initiation threshold  $a_t$ . The exact means by which the transformation from hillslope to channel occurs appears to be unimportant, though Willgoose and co-workers have extensively used one that results in channels being permanently formed at a point once the threshold has been exceeded at that point. More important is the functional dependence of the channel initiation function on discharge and slope which Willgoose and co-workers have formulated as

$$a = \beta_5 q^{m_5} S^{n_5} \quad 1.3.4$$

where  $a$  channel initiation function  
 $\beta_5, m_5, n_5$  coefficients

Again, within the conceptual framework of the model, the form of the channel initiation function can be formulated as seen fit in light of physical processes observed in the field. The formulation above results from consideration of surface flow driven channel formation processes where it has been postulated that channel formation occurs when a critical velocity or tractive force is exceeded by overland flow or where the head gradient in the groundwater exceeds a specified piping threshold (Willgoose et al 1989). It is consistent with field data collected by other workers (Montgomery & Dietrich 1988, Patton & Schumm 1975). This relationship will be calibrated in section 4.4 of this report using preliminary data from Tin Camp Creek.

The channel network calculated by the model is used to determine the rate at which fluvial sediment transport occurs as

$$f(Y) = \begin{cases} \beta_1 O_t & Y = 0 \text{ (hillslope)} \\ \beta_1 & Y = 1 \text{ (channel)} \end{cases} \quad 1.3.5$$

where  $Y$  channel indicator variable  
 $\beta_1$  erosion rate constant  
 $O_t$  ratio of hillslope to channel erosion rate

The transport rate  $\beta_1$  can be spatially variable in any predefined way; structural controls due to the differential erodibility of strata can be easily modelled. However, the sediment transport rate  $\beta_1$  is not varied as a result of the evolving catchment's hills and valleys so that differential

sediment transport rates in valleys and interfluvies cannot be modelled other than with a crude area or slope dependence. Very little data are available to calibrate such a dependence. The parameter  $O_t$  is generally assumed to be somewhat less than 1 and this reflects the increased velocities, and thus transport rates, in channels over that occurring on the hillslopes. Diffusive transport is assumed to occur at the same rate on both hillslopes and channels.

Note that the sole use of the channel network *within the model* is in determining the differential rates of erosion that occur in the channel and on the hillslopes. No field interpretation is made regarding whether a channel head is an abrupt or gradual transition, only that the fluvial transport rate changes abruptly. Willgoose and co-workers have normally assumed that the actual channel network observed in the field and the channel network postulated in the model are synonymous.

In summary, the important feature of the presented model—the one that distinguishes the networks it generates from other stochastic network generation models (Leopold & Langbein 1962, Howard 1971)—is that the network extension process is governed by physical conditions: the drainage pattern on the hillslopes and the local slopes in the hillslopes around the channel head. That channels can be assumed to erode faster than the hillslopes facilitates the natural tendency towards convergence of flow on the hillslopes around the channel heads. The pattern of pre-existing channels governs the valley erosion, which in turn governs the drainage pattern of the hillslopes and their slopes, and thus, the spatial pattern of the channel initiation function. This complicated interaction of flow and sediment transport in both the channels and hillslopes over long time scales is central to the channel network extension process and it gives catchments their form.

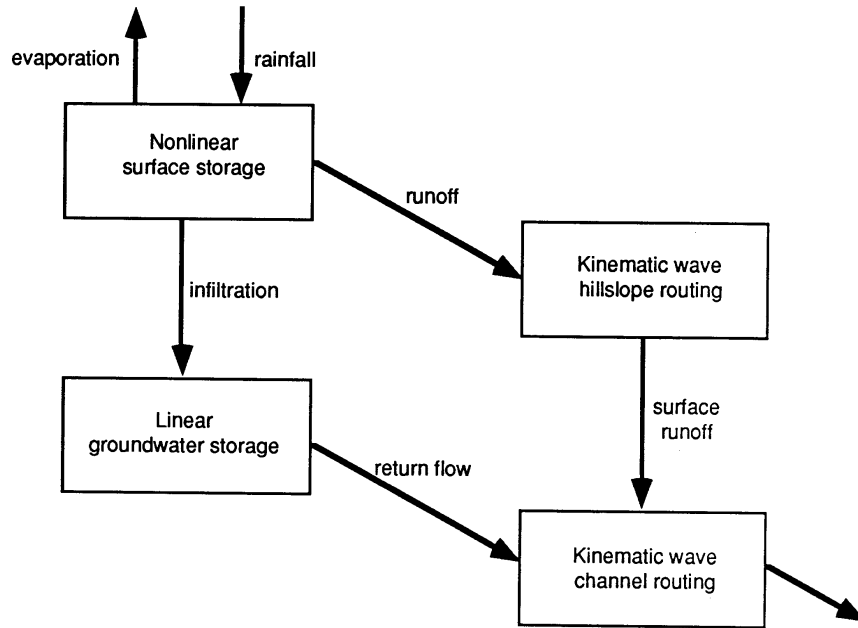
#### **1.4 Hydrology model**

Runoff is the most important determinant of soil erosion. Thus it is important to simulate runoff as accurately as possible to provide a reliable erosion assessment. To do this a digital terrain based rainfall-runoff model will be calibrated to the field data collected at experimental sites on the spoil. This model will then be used to calibrate the runoff required by SIBERIA. The model will also be used to simulate the long-term runoff series that will be used to determine the relationship between the short-term erosion rate measured during runoff events and the long-term erosion over the historical range of runoff events.

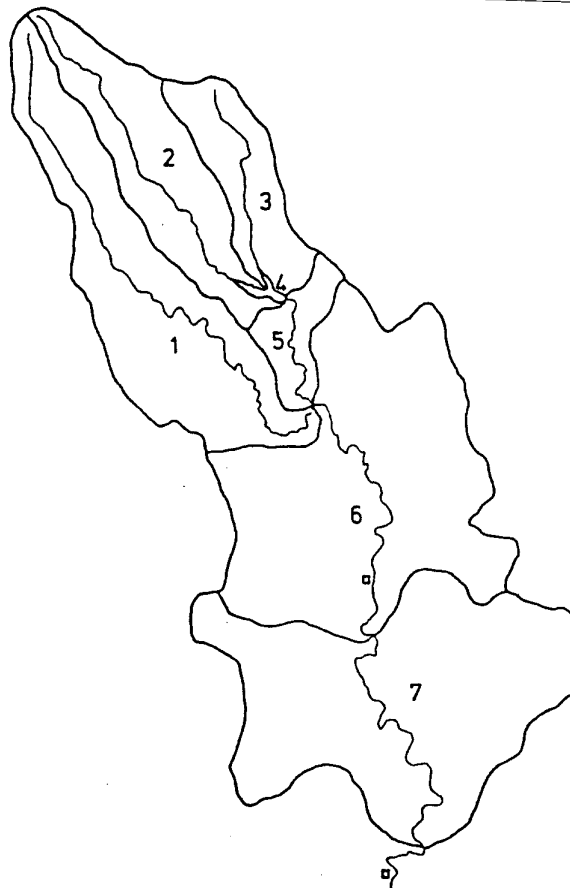
The hydrology model used to fit to the rainfall simulator and natural rainfall plots is based on the 1-D kinematic wave flood routing model described by Field and Williams (1987) called the Generalized Kinematic Catchment Model (GKCM). This model is a conceptual rainfall-runoff model (fig 1.1) that breaks the catchment up into a number of subcatchments connected together with a channel network (fig 1.2) draining to a single catchment outlet. More specifically it includes:

- 1 Nonlinear storage of water on the hillslope surface
- 2 Philip infiltration from the surface storage to a linear groundwater store
- 3 Discharge from the surface storage to the channel
- 4 Discharge from the groundwater storage to the channel
- 5 Routing of the runoff down the channel by use of the kinematic wave

This form of the model has been tested on a number of catchments and has been shown to give satisfactory results. As conceptualised by the developers this model is a Hortonian runoff model.



**Figure 1.1** Conceptual arrangement of the Field-Williams rainfall-runoff model as extended by Willgoose (DISTFW)



**Figure 1.2** Typical division of catchment into subcatchments (from Field & Williams 1987)

This model has been extended to use digital terrain elevation data on a square grid; hereafter this new extended model will be called the Distributed Field-Williams Model (DISTFW). Each grid point is considered to be a subcatchment and drainage from node to node and through nodes occurs by a kinematic wave on the overland flow. For the purposes of this project the modifications to the model include:

- 1 The drainage pattern from node to node is determined on the basis of the steepest slope direction using the same algorithm used in SIBERIA.
- 2 The groundwater component on the model has been disabled. Infiltration is assumed to drain to a very deep aquifer which does not discharge to the surface within the study site. This is believed to be a good representation of the waste rock dump.
- 3 The area associated with each subcatchment (node) is equal and equal to the square of the grid spacing. The DTMs provided for the waste rock dump are on a 30 m grid so that the area of each node is 900 m<sup>2</sup>.

This extended model maintains the conceptualisation of Hortonian runoff but by using the digital terrain extensions it is possible to model subsurface saturation runoff using the methodology of Moore and Grayson (1991). The subsurface saturation runoff mechanism is not considered important on the waste rock dump because of the lack of a well developed soil profile exhibiting decreasing hydraulic conductivity with depth and underlying impermeable bedrock layer.

## 1.5 Erosion model

The overland flow erosion model used to fit the erosion data is one commonly used by geomorphologists and soil scientists. It is of the general form

$$q_s = \beta_1 q^{m_1} S^{n_1} (\tau - \tau_c) \quad 1.5.1$$

where	$q_s$	sediment discharge/unit width
	$q$	discharge/unit width
	$S$	local slope
	$\tau$	bottom shear stress for the flow
	$\tau_c$	shear stress threshold

The parameters  $\beta_1$ ,  $m_1$  and  $n_1$  are fixed by the flow geometry and erosion physics. This equation parameterises the total load; ie the sum of both the suspended and bed loads. For instance, for a constant width channel with sediment transport according to the Einstein-Brown equation  $m_1 = 1.8$  and  $n_1 = 2.1$ . For flow in rills the parameters are approximately  $m_1 \approx 1.3$  and  $n_1 \approx 2.2$  (Moore & Burch 1986, Willgoose et al 1989). Exact values for these parameters depend on the rill geometry. The parameter  $\beta_1$  gives the rate of sediment transport and is primarily a function of sediment grain size.

Riley (1992) attempted to identify a shear stress threshold as in equation 1.5.1 for the material from the waste rock dump using a small flume and concluded that the value was very small, and that he was unable to reliably estimate it. On this basis the shear stress threshold in all the work that follows will be assumed to be zero.

We also note that bottom shear stress,  $\tau$ , can be described by a function of discharge and slope (ie Willgoose et al 1989) so that the sediment transport model that is used here has the form

$$q_s = \beta_1 q^{m_1} S^{n_1} \quad 1.5.2$$

This model does not incorporate hysteric effects in the sediment rating curve that may result from sediment storage. However, since there is no data for the region that indicates the possible importance of this effect over areas of the size of the waste rock dump this effect has been ignored. It is not possible at the current time to predict the magnitude of this effect without extensive field data for large catchments.

For smaller areas the overland erosion is dominated by rainsplash, or rain-flow, erosion. Rainsplash is generally modelled by an additive Fickian diffusion term where the diffusivity,  $D$ , is a function of the applied rainfall energy (in turn a function of the energy of the individual raindrops and the rainfall rate) so that  $D = D'R$  where  $R$  is the rainfall rate. The total erosion rate is then given by the expression

$$q_s = \beta_1 q^{m_1} S^{n_1} + DS = \beta_1 q^{m_1} S^{n_1} + D'RS \quad 1.5.3$$

For calibration, this result is more conveniently expressed in terms of the concentration

$$c = \beta_1 q^{m_1-1} S^{n_1} + \frac{DS}{q} = \beta_1 q^{m_1-1} S^{n_1} + \frac{D'RS}{q} \quad 1.5.4$$

These equations indicate that as the discharge decreases, or the area of the plot decreases, then the second, diffusive term will begin to dominate the expression for concentration. For large areas the diffusive term becomes relatively less important. That the diffusive term is additive implies that the processes that cause diffusive transport and those that cause fluvial transport do not interact. Thus a higher or lower level of diffusive transport does not of itself change the rate of fluvial transport.

In using SIBERIA it is necessary to clearly distinguish between the instantaneous sediment transport rate and the long-term sediment transport rate. The instantaneous transport rate is that which is measured at some instant in time, for instance, within a runoff event by a grab sample. This is the quantity that is measured during field trials. The long-term sediment transport is the average rate of transport of sediment per year; the average of all the erosion events during the year. As well as being a function of the short-term rate, this quantity is a function of the average runoff properties and climate of the catchment. Willgoose et al (1989) showed that if the sediment transport rate was described by equation 1.5.2, then the long-term average could also be expressed in that form. The interpretation of  $\beta_1$  and  $q$  are modified ( $\beta_1$  is a frequency factor and  $q$  is the mean peak discharge) and the runoff modelling of this report is aimed at simulating this runoff data for the waste rock dump.

The model of equation 1.5.1 is primarily used for 'transport limited' sediment transport. That is, it is assumed that there is always sufficient material on the surface to satisfy the transport demands of the flow. This is not the case when sediment starvation or source limitation occurs and it is not established that equation 1.5.1 is necessarily complete for this case. There does appear to be some evidence to suggest that sediment starvation can occur at Ranger (Riley, in prep). Riley (1992) showed that for a constant discharge the concentration of sediment decreased over a period of 1 hour but the effect appeared to be small. Moreover, some of the concentration data for the natural rainfall events exhibited clockwise rating curves with discharge. However, if the sediment transport model is calibrated to the natural data rather than simulated runoff data, this effect will be accounted for, on average, in the calibration. For natural runoff events, the recorded data will be for the naturally sediment starved flow; the calibrated  $\beta_1$  will be lower, reflecting the sediment starvation. If, however, the sediment

transport model is calibrated with the rainfall simulator trials then sediment starvation has to be accounted for explicitly. This study uses the natural data wherever possible to circumvent this problem. In any event, the small differences between the simulated rainfall and natural rainfall concentration data appear to have negligible effect on the relationship between discharge and concentration.

## 2 Hydrology model calibration

### 2.1 Overview

#### 2.1.1 Data

Natural rainfall runoff events for the caprock and batter sites were supplied by staff of the Geomorphology Branch at *eriss*. Tables 2.1 and 2.2 summarise the runoff and rainfall data that have been used in this study. Maps of the field sites are provided in appendix A and the data are tabulated in appendix B. Catchment characteristics are summarised in table 2.3.

Some of the rainfall and runoff data were checked by double mass curves. A very good correlation was found for most storms (see fig 2.1 & 2.2) as would be expected by their closeness. For the 16/2/91 event, the batter gauge appears to have missed the first peak of a two-peaked storm.

The plot characteristics (eg area, slope) were determined from the contour maps in appendix A.

**Table 2.1** Runoff data supplied for caprock and batter sites<sup>(c)</sup>

Storm	Caprock sites <sup>(a)</sup>					Batter sites		
	WT1	WT2	WT3	RT1	OUT	RT2	WT1	WT2
25/12/90								
28/12/90								
7/1/91 (20:50) <sup>(b)</sup>	?				✓ <sup>(d)</sup>			
7/1/91 (14:55) <sup>(b)</sup>		✓		✓	✓ <sup>(d)</sup>			
8/1/91					✓ <sup>(d)</sup>			
10/1/91 (7:55) <sup>(b)</sup>	✓	✓		✓	✓ <sup>(d)</sup>			
10/1/91 (14:00) <sup>(b)</sup>					✓ <sup>(d)</sup>			
11/1/91					✓ <sup>(d)</sup>			
21/1/91	✓	✓						
27/1/91								
28/1/91					✓ <sup>(d)</sup>			
30/1/91								✓
4/2/91		✓					✓	
6/2/91			✓			✓	✓	✓
13/2/91						✓		
16/2/91	✓		✓			✓	✓	✓
22/2/91						✓	✓	

(a) Site notation as per Neave (1991); (b) Two events supplied for this day, approximate beginning time in 24 hour clock; (c) Notation is ✓ = data appears to be accurate; × = data appears to be inaccurate; ? = data conflicts with other data; (d) Data is truncated above discharge 15 L/s.