4.0 Model Calibration and Predictions

4.1 Theory

The computer model SIBERIA was developed to study the link between physical process and the development of catchments. The distinction between hillslope and channel based processes is considered some of the most important aspects of this model.

As outlined above, the major components of the model focussed on in this study simulates the evolution of catchment elevations over time by continuity of mass, in this case the batter slope.

Fluvial erosion processes, modelled according to standard forms, is incorporated into influx and outflux of regions within the catchment over time.

Average elevations are therefore determined over monitoring period based on the following governing equation.

$$\frac{\partial z}{\partial t} = \frac{\nabla q_s}{\rho_s(1-n)} + D.\nabla^2 z \qquad \text{(adapted from 1.3.1)} \qquad (4.1.1)$$

where

z = elevation,
t = time,
q_s = sediment transport per unit width,
$\rho_s(1\text{-}n)$ = bulk density of sediment
D = diffusivity of diffusive transport (rainsplash, landslide)

The differential equation is described as a continuity of sediment transport over time, with other components of the governing equation such as tectonic uplift and diffusion terms were neglected for this study. This was considered reasonable since the monitoring period was short, and surface wash erosion was the most commonly observed mechanism. Only the exposed sidewalls of the lower sections of the gully were sufficiently high for landslip mechanisms to occur, and these areas were not considered important for simplification of modelling process.

The more sophisticated methods of diffusion such as soil creep, landslide and rainsplash were considered negligible, as mass transport processes observed were almost entirely dependent on fluvial transport.

The sediment transport process q_s, is modelled by the second term in equation 4.1.1, and can be represented in a number of ways

$$q_s = f\left(S^n, q_w^{\,m}\right) \qquad (4.1.2)$$

where

q_s = sediment flux, g/s
q_w = discharge, L/s
m, n = derived exponents
S = Slope, m/m

with equation 4.1.2 reflecting findings from both field and laboratory observations by soil scientist and geomorphologists. The general form of this model is:

$$q_s = \beta_1 q^{m_1} S^{n_1}(\tau - \tau_c) \qquad (4.1.3)$$

where

q = discharge per unit width,
β_1 = rate constant for sediment transport, function of sediment grain size,
m_1,n_1 = derived exponents,
τ = bottom shear stress for the flow,
τ_c = shear stress threshold (critical shear stress)

However for the material from the waste rock dump the critical shear stress has been attempted to be identified Willgoose *etal,* 1993, and their conclusions were that its value was indistinguishable from zero, with this conclusion adopted in parameter estimation.

Implications as to the nature of the rehabilitation design adopted will incorporate extensive revegetation, in doing so will reduce the erosional force of surface flow significantly. Plants provide protection of the surface by cohesion, and binding of soil particles, increasing the resistance to scouring. Prosser, 1996 suggests that the critical threshold for incision can be several times higher on vegetated surfaces compared to that of bare surfaces, although as stated, this is not considered in this study with minimal vegetation evident on either study site.

Equation 4.1.3 parameterises the total sediment transport, including bed load and suspended sediment loads (as defined above).

Exact values for these parameters has been the focus of previous studies conducted on site such as Willgoose *etal*, 1992, and Evans in prep.

Natural rainfall runoff events and simulated rainfall catchments (largest area ~ $100m^2$) were used to calibrate the fluvial sediment transport equation (equation 4.3.2) and were shown to be least dominated by diffusion processes (as assumed above). These small scale erosion plots were located on the Northern WRD adjacent to the cap site as described in Section 2.2, with other study sites on the batter slope itself, Willgoose *etal*, 1993.

The parameters fitted to equation 4.1.3 were n_1, m_1, and β_1, where m_1 and β_1 relate directly to estimates of sediment loss for monitored fluvial erosion studies. The exponent n_1 of the slope term S is derived using the following relationship (Evans, Willgoose, and Riley, 1995):

$$q_s \propto \frac{1}{d^{3/2}} \qquad (4.1.4)$$

where
d = median sediment grain diameter (mm)

Evans *et al*, 1995 suggests that this function of Einstein-Brown relationship can be adapted to determine a value for the WRD,

$$\left(\frac{S_{Cap}}{S_{Batter}}\right)^{n_1} = \left(\frac{d_{Cap}}{d_{Batter}}\right)^{1.5} \qquad (4.1.5)$$

where
S_{Cap} = cap site slope from previous studies (S_{Cap} = 0.028),
S_{Batter} = batter site slope (S_{Batter} = 0.207),
d_{Cap} = mean diameter size (d_{50} Cap: 0.54mm),
d_{Batter} = mean diameter size (d_{50} Batter: 1.39mm).

Estimate of n_1 based on these values is 0.71 (with 0.69 from Willgoose *etal*, 1993).

This value for n_l is then adopted and included in the multiple regression analysis used to determine m_l, and β_l as described by Evans *et al*, 1995.

$$\log T = \log \beta_1 S^{n_1} + x.\log \int Q^{m_1} dt \text{ (Evans } etal\text{, 1995 equation 11)} \qquad (4.1.6)$$

For this case, the value of n_l is considered susceptible, since the mean particle diameter, d_{50} varies dramatically once erosion commences.

For sediment transport according to the Einstein-Brown equation in a wide channel, the parameter values for m_l and n_l are 1.8 and 2.1 respectively. Investigation into the sensitivity of the estimate of the exponent on the slope component n_l is conducted below, although a value of 2.1 is initially adopted due to the stability of preliminary modelling results.

From equation 4.1.6 above, the regression analysis is used to determine all the components of the sediment transport equation. By taking S^{n_1} as a known value, the parameter β_l can be determined, as the *log K* term is devised from the analysis process. Thus the estimate of the parameter n_l influences the erodibility of the material in parameter β_l as well as the contribution to total sediment loss within the slope component.

Evans *etal*, 1995 noted that regression analysis for total sediment loss of:

$$T_B \text{ (batter)} = 3.34\, S^{0.71} w^{-0.8} \int Q^{1.8} dt \text{ } (R^2 = 0.53;\ df = 11;\ p < 0.01)\text{, and}$$

$$T_C \text{ (cap)} = 13.8\, S^{0.71} w^{-0.8} \int Q^{1.8} dt \text{ } (R^2 = 0.53;\ df = 11;\ p < 0.01). \qquad (4.1.7)$$

with erroneous data points removed, this relationship was analysed again.

$$T_B \text{ (batter)} = 5.05\, S^{0.71} w^{-1.8} \int Q^{2.8} dt \text{ } (R^2 = 0.93;\ df = 9;\ p < 0.001)\text{, and}$$

$$T_C \text{ (cap)} = 20.9\, S^{0.71} w^{-1.8} \int Q^{2.8} dt \text{ } (R^2 = 0.93;\ df = 9;\ p < 0.001). \qquad (4.1.8)$$

where

$$T(g) = \beta_1 . S^{n_1} . w^{(1-m_1)} . \int Q^{m_1} dt$$

with $\int Q^{m}{}_{l}$ = Cumulative value of duration of event,
T(g) = Total sediment loss.

Evans *etal*, 1995 notes that the value suggested for the exponent m_1 at 2.8 does not compare well with previous studies by Willgoose *etal*, 1993 with their estimate of m_1 at 1.68. The estimated value for parameter exponent n_1 from equations 4.1.8 was 0.71 and compares well with previous studies, with a value of 0.69 being determined.

The results of this process, conducted previously by Willgoose *etal*, 1993, is expressed in the following fitted relationship ($r^2 = 0.64$),

$$c = 3.59\, q^{0.68} S^{0.69} + \frac{0.178RS}{q} \quad \text{(Willgoose etal, 1993 equation 5)} \quad (4.1.9)$$

where

c = sediment concentration = q_s / q, (g/L)
q = discharge = $f(q, S, Area)$, (L/s),
q_s = sediment flux, (g/s).

From equation 4.1.9 and above, the fitted parameter values adopted were $\beta_1 = 3.59$, $m_1 = 1.68$, and $n_1 = 0.69$, (and 2.1 for comparison). Rainsplash diffusivity was neglected and these results were considered consisted with other field data accumulated by the geomorphology group at ***eriss***.

The next important component of the calibration and adaptation process is the derivation of discharge, **q** in equation 4.1.9. The discharge relationship is a function of area, slope and surface discharge. In this case the drainage pattern of the catchment is adapted to represent the gully catchment as a series of nodal entry points at the top of the initial batter surface, with the slope of the gully catchment neglected, due to the nature of the constructed reservoir above the head of the gully and the assumption from this that the surface is almost completely flat (slope is 1 to 2% on site).

$$Q = \beta_3 . A^{m_3} \quad (4.1.10)$$

where

Q = average discharge for 1 hour of each of the storm events,
À = area of the gully catchment,
m_3 = exponent on the area in discharge used in sediment transport,
β_3 = coefficient between discharge and area used in sediment transport.

The discharge per unit width term, **q** was evaluated to be the discharge entering the head of the gully network averaged over the duration of the storm. The average discharge over a 1 hour period, for each of the storm events was used to determine the parameter β_3, with exponent m_3 representing a non-linear relationship with area, disabled ($m_3 = 1$).

$$\beta_3 = \frac{\text{discharge average in 1 hour}}{\text{area of gully catchment}} \tag{4.1.11}$$

The runoff module within SIBERIA does not directly model runoff, with no continuity of water or runoff routing routine within the model. For this case, a user-specified runoff module was adopted with this representing a series of feed points located at the head of the gully network, at the outlet of the gully catchment. This constituted the discharge-area relationship discussed in equation 4.1.10 above, being applied initially at the 2 or 4 inlet points of the constructed initial landscape.

The parameter β_3 is equivalent to 'mm' of rainfall, and was calibrated for each storm event, whilst it is also noted that β_3 only appears in the discharge-area relationship used in SIBERIA and is representative of the average storm duration of 1 hour.

The coefficient β_1 of the sediment transport equation, represents the erodibility of the waste rock material, and was determined using site specific data and is considered the final component of the calibration process.

The bulk density, ρ_s (1-n) from equation 4.1, for the waste rock material was determined from soil analysis conducted at three locations on the batter slope. The β_1 value, derived from erosion studies and the devised bulk density estimate are combined in the β_1 coefficient used for SIBERIA in equation 4.1.12, with derivation appearing in Appendix D.

From equation 4.1.1, the sediment transport equation was calibrated as follows:

$$\beta_1(siberia) = \frac{\beta_1}{\rho_s(1-n)} \cdot \frac{60s}{\min} \tag{4.1.12}$$

where

$\rho_s(1\text{-}n)$ = bulk density,
beta_1 = sediment transport coefficient from equation 4.1.9,
time = conversion factor for timestep from 1 hour to 1 minute.

The value of bulk density was used to derive the erodibility coefficient in SIBERIA, with time step reduced from 1 hour duration (derived from the 1 hour duration β_3 discharge relationship) to 1 minute.

It was also noted numerical stability requirements dictated iteration timestep length, within the SIBERIA program, was set to be 0.05 for model simulations presented.

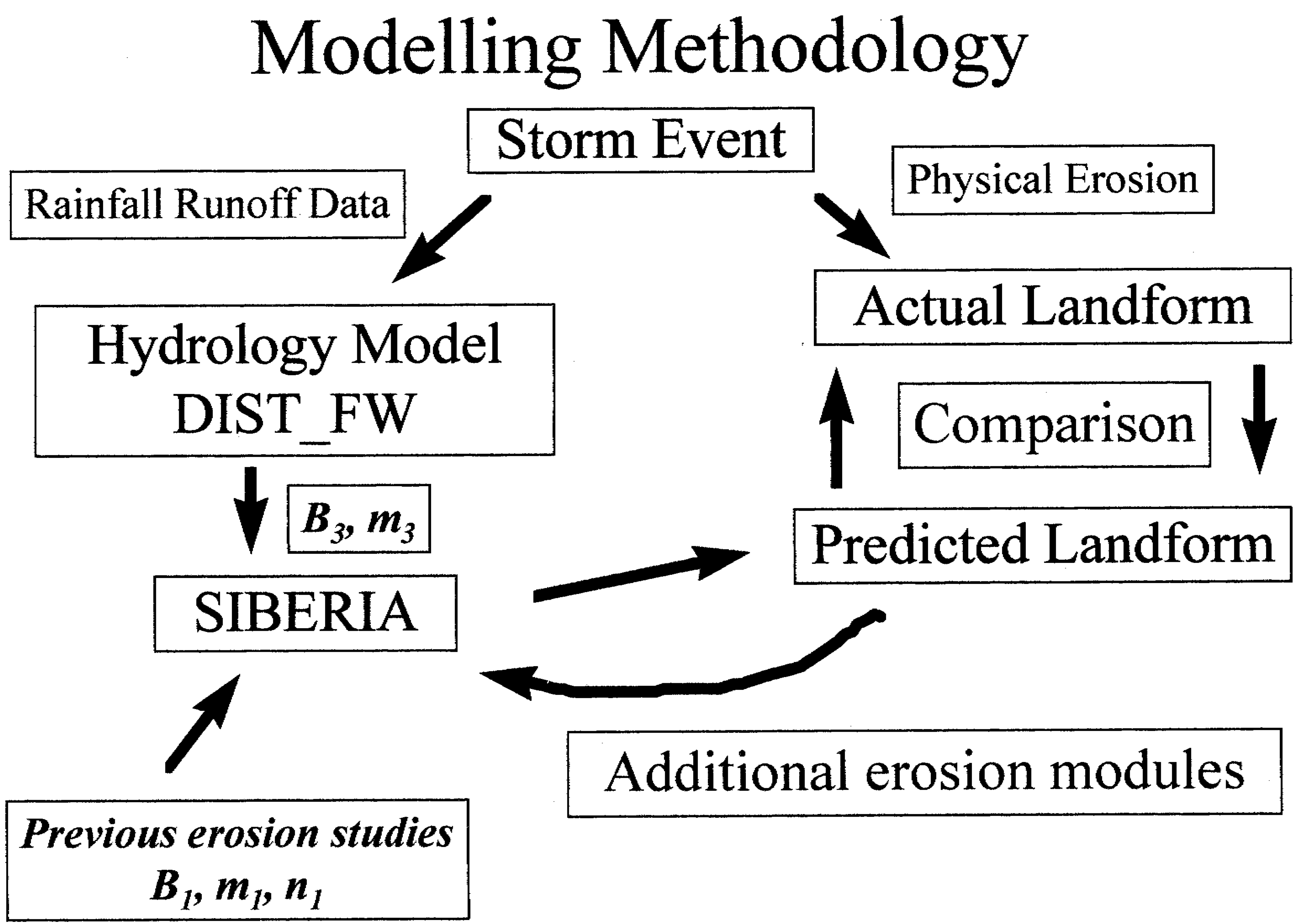

Figure 4.1: The combination of the two major model components, from hydrology and sediment erosion models, allowed the calibration of the landform model SIBERIA to be representative of the batter slope study site. The runoff model was instigated using a series of inlet points across the top of the batter slope, with erosional characteristic (β_1, m1, and n1) of the site adapted from previous studies.

4.2 Initial Surface and Determination of Parameters

The evolution of the batter slope over the 96-97 Wet Season was intensively monitored. Hydrological data was adapted to represent the three storm events that initiated and altered the gully significantly.

The initial surface was created to approximate the geometry of the batter slope, and gully catchment with runoff from the catchment entering the head of the batter slope from an outlet cut into the bund wall (Section 2.2).

The profile of the batter slope has been described as complex, with 2 approximations being made. The first surface incorporates a small section of the gully catchment, with the top of the surface extending back about 10m into the catchment.

The other alternative did not include the upper section of the catchment, and effectively represented only the study site area. Both of these alternatives are illustrated in Figure 4.2.1 and 4.2.2 respectively.

From Figure 4.2.1, the study area was approximated to a 20m by 60m rectangular grid, closely resembling the transect measurement sections described in Section 2.0. Grid spacing of 1m simplified the calibration of the initial parameters for SIBERIA with each grid representing an area of $1m^2$.

The inlet points were located at points (9,60) and (10,60) for the initial discretisation, with a wide inlet point scenario also considered, with inlet points across points (8,60) to (11,60). The outlet point, as described in Figure 4.2.1, was located at the base of the slope and was assumed to be fixed elevation at points (8,2) to (11,2). The elevations at the entry points to the batter slope were assumed not to be fixed.

Both surfaces were evaluated during the modelling process with theoretical behaviour approaching equilibrium profile of the slope with these surfaces constructed using from results devised from survey conducted during monitoring period. The elevation profile is represented in Figure 4.2.1, and Figure 4.2.2, with nature of slope, rising to elevation of 13m.

The initial profiles were created with another small fortran program named CREATERST2.f and detailed listings of the derivation and implementation are contained in Appendix E.

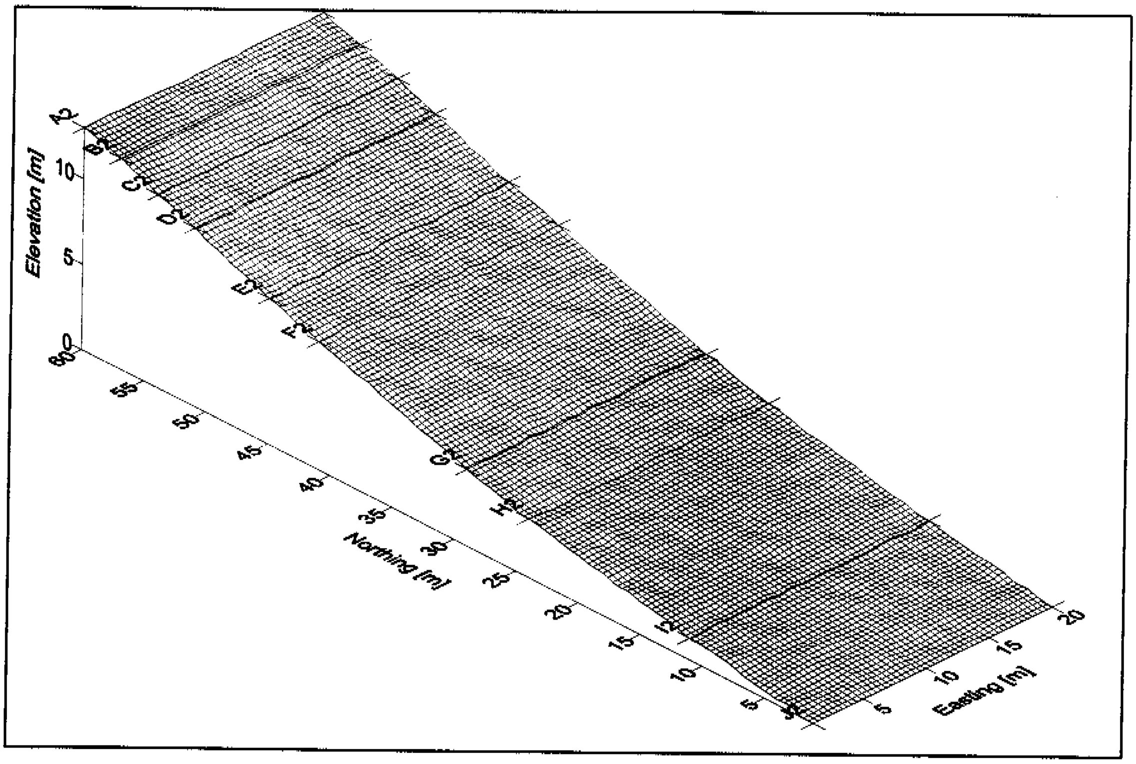

Figure 4.2.1: Initial surface incorporating flat sloping upper section, representative of the catchment outlet point . Feed points for runoff module were set at the extreme left end at the approximate location of the outlet point.

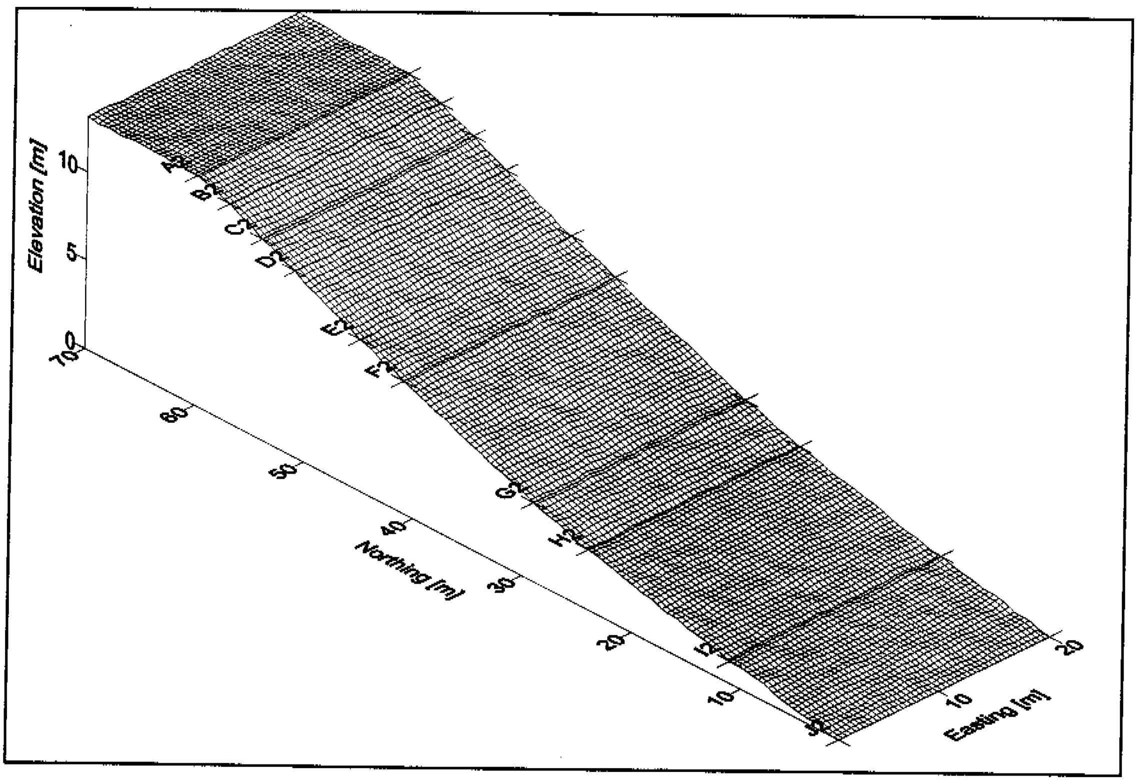

Figure 4.2.2: The other alternative for the initial landform profile did not represent the upper section of the catchment outlet. The inlet feed points of the batter slope appear along the top of the study area.

There are a large number of parameters in SIBERIA, and these control the modes of operation of the model, actual physical parameters, and numerical behaviour of the model. Willgoose, 1992 notes that there are 20 integer parameters and 50 real parameters, with many not presently used but present to allow continuing development of the model. Other input requirements are user defined modules representing the runoff module, and armouring module. Figure 4.2.4 below illustrates the typical format used to present the parameters values adopted for each of the modelling scenarios detailed in Section 4.3.

Many parameters were not altered during the modelling process. Parameters such as β_3, and the initial surface profiles were altered after each storm event, and other user defined modules were incorporated into investigation of different modelling scenarios. The definition of each of these parameters, illustrating default values if they are not

```
SIBERIA      8.01
     60     10     20     60      0      0
      5      1      0      1      0      2        <-- Integer Parameters
      0      0      1      0      0      0
      0      0
   0.000000   1.000000   0.000000   0.000000   1.000000
   1.000000   0.000000   1.000000   0.100000   0.000000
   0.000000   0.000000   0.000000   0.000000   0.005000
   1.000000   1.000000   0.002720   0.112000   1.680000
   2.100000   1.930000   0.010000   2.500000   0.300000    Real Parameters
  10.000000   0.400000   0.100000   2.000000   1.000000
   0.000000   1.000000   1.000000   1.000000   0.000000
   0.000000   0.000000   0.000000   0.000000   0.000000
   0.000000   0.000000   0.000000   0.000000   0.000000
   0.000000   0.000000   0.000000   0.000000   0.000000
f.dat
        <-- User Defined Modules

                 Fixed Elevation Points
   4
   8 2                Random Multiplier Field              Elevation
   9 2
   10 2                                                    Drainage Direction
   11 2
.0000E+00 1.0000 0.0010 0.1414251E+00    0  5 0.0000E+00 0.0000E+00
```

Figure 4.2.4: Parameters allocated for each of the modelling scenarios are illustrated below using this format. It is noted that parameter value used during each of these scenarios did not alter significantly during the modelling process.

presented below, appears in Willgoose, 1992.

RunT: (#1)

Total time length for duration, set to be 60 minutes, as timestep calibrated to 1 minute periods.

OutT: (#2)
Statistics output duration, set to be 10. This produces a statistical summary of the iteration process, at every 10 timesteps, in this case 10 minutes.

Kx, Ky : (#3 and #4)
Grid coordinates are 20m by 60m, with grid size effectively $1m^2$.

ModeS: (#7)
The mode of solution of the sediment transport equation using explicit or analytic solids. For all cases this was set to be 5.

ModeRn: (#10)
Enabled random perturbations instigated in the initial surface landforms *.rst2 files to be read. For all cases this was enabled, as different surface profiles were used. The multiplier factor is illustrated in Figure 4.2.4 above, with default value of 1.

UserRO: (#12)
This module is activated by UserRO, where the integer parameter refers to either 'f.dat' or 'fwide.dat' representing the two alternative water source entry points. This routine is illustrated in Figure 4.2.5 below, and involves coordinates of the inlet points and amount of area (number of nodes) contributing to each of the points. It was highlighted that the total area was $7200m^2$, with each node equivalent to 3600 nodes for the narrow feed point, and 1800 nodes for wide inlet point. Inlet points incorporating the upper section of the gully catchment into the initial surface were between (8,70) and (11,70) respectively.

UserFT: (#11)
This module is similar to UserRO, with user defined sediment transport rate incorporating the rudimentary armouring component into the model, Figure 4.2.6.

```
SIBERIA RUNOFF
1ST LINE
2ND LINE          <-- Narrow Inlet Standard
3RD LINE              Profile: 20 by 60.
2
9 60 3600 1
10 60 3600 1

SIBERIA RUNOFF
1ST LINE
2ND LINE              Wide Inlet with Extended
3RD LINE              Profile: 20 by 70.
4
8 70 1800 1       <--
9 70 1800 1
10 70 1800 1
11 70 1800 1
```

Figure 4.2.5: The used defined runoff module replicates the gully catchment behind the 2 or 4 inlet points at the top of the batter slope. Filename 'f.dat' or 'fwide.dat', appears in Figure 4.2.4, with total contributing area of 7200 m^2 (equivalent to nodes) representing an inflow of 7200/4 or 7200/2 for each inlet point.

The spatially constant mode was adopted for all cases except when considering armouring component. Inclusion of the depth erodibility relationship involved setting this mode to 1 from default value of 0 (Section 4.4).

The exponential relationship between erodibility (measured as function of mean grain size) and depth used to derive these coefficients, are used to multiply the calculated depth of erosion within the SIBERIA model before evaluating new elevations.

This relationship effectively reduces erosion with depth, however cannot distinguish at this stage between previously eroded material, or unsullied hillslope.

```
1ST LINE
2ND LINE              Depth Coefficient, C ~ 15,
3RD LINE              and exponent, m ~ 1.
15.0 1.0      <--
```

Figure 4.2.6: The user defined erosion module involved setting the integer parameter, UserFT from 0 to 1. The implementation of this module involves two coefficients used in an exponential relationship between erodibility and depth.

The remainder of the modules (integer parameters) were not considered or altered during the modelling process, and were set at default values.

The next group of parameters were the real parameters, which allocated numerical values to each of the coefficients, and exponents used in the sediment transport model, discharge-area relationship.

$1/a_t$: (#27)
The channel initiation threshold was set to be 0, such that a channel would not be formed, and the channelisation (different sediment transport equation) not implemented.

The differential erosion rate of the hillslope and channel was not considered in this study, with channelisation module disabled for all model simulations.

m_3: (#37)
The discharge-area relationship is assumed to be linear, with m_3 taken to be unity.

β_3: (#38)
The coefficient in the discharge-area relationship, equation 4.1.10, was determined from the gully catchment outlet points at the top of the batter slope. For each of the storm events the following values were adopted, with consequent storm events run in series.

Table 4.2.1: The coefficient in the discharge-area relationship was adapted to represent the outlet of the gully catchment. Duration of each storm event were averaged over 1 hour, whilst the event on 230197 was considered to maintain intensity for entire hour, although event only lasted 25 minutes.

Event	Average Discharge (m^3/hr)	β_3
261296	19.59	2.72×10^{-3}
010197	14.33	1.99×10^{-3}
230197	22.75	3.16×10^{-3}

β_1: (#39)
The coefficient in the sediment transport equation, equation 4.1.9, was adapted using the bulk density determined on-site to be 1.93gcm^{-3} in equation 4.1.12 above. The value adopted was 0.112 and represented the erodibility of the surface material within the SIBERIA program.

m_1: (#40)
The exponent on discharge in sediment transport equation was evaluated using equation 4.1.9 from fitted erosion studies at value of 1.68.

n_1: (#41)
The exponent on slope in sediment transport equation is discussed in Section 4.1 above, where a value of 0.69 from equation 4.1.9, or the default value of 2.1 being adopted during the initial modelling period. Sensitivity analysis of the effect of this parameter will be conducted initially, and using the final simulation scenario comparing all of the implemented modules.

time: (#43)
Iteration time step was set at 0.05 for the majority of simulations conducted, for numerical stability, resulting in computational time lengths of about 25 minutes per storm event.

The modelling process involved the approximation of an initial surface, with the addition of random noise to elevations used to simulate the relatively uniform topography, whilst representing the nature of the waste rock material. This is illustrated in Figure 4.2.1, and Figure 4.2.2 above.

4.3 Simulations

The implementation of parameters into the SIBERIA model was varied to test the capability of the model to predict size and shape, as well as characteristic of the behaviour of gullies formed. By comparison between predictions from SIBERIA to the actual formation, the impact of different mechanisms, and the determination of important parameters could be conducted.

A number of simulation scenarios were investigated to assess the various aspects of erosional mechanisms. These simulations include firstly a standard case, by which the remained of simulations are compared, incorporation of the gully catchment, increase in the width of the inlet points, introduction of random erodibility in the waste rock material, as well as the assessment of the rudimentary armouring model and determination of sensitive parameters such as the slope exponent n_1.

Standard

The initial surface created to represent the batter slope marks the first stage in assessing model behaviour and predictions. The relationships outlined above, are used to derive the parameters required for the SIBERIA model, with this case specifically representing a standard by which all the other simulation scenarios are compared.

This surface effectively represents a uniform, homogenous material, with fixed outlet point, and the armouring module disabled.

The gully catchment was represented by the user defined runoff module described in Figure 4.2.5 above, with 'f.dat' being adopted for the study site (Figure 4.2.2), and 'fup.dat' being adopted for the extended study site incorporating the gully catchment (Figure 4.2.1).

Increased Width

The impact of increasing the at the top of batter slope was investigated. The total contributing area, representative of the gully catchment was 7200m^2 (equation 4.1.10), with standard runoff module 'f.dat' in Figure 4.2.5 replaced with 'fwide.dat'.

The 'fwide.dat' runoff module distributed the surface flow from the catchment across 4 nodes, instead of 2 nodes for the narrow feed case. Although the total flow is not altered and the erodibility of the surface material remains unchanged, the wide entry point may reduce the extensive erosion observed in preliminary modelling results, with the head of the gully eroding to depths in the order of 2 to 3m. The discretisation of the batter slope into a 20 by 60, $1m^2$ grid, may not be conducive for the development of more than one gully, as the flow-path from the 4 inlet points may concentrate to one within only a few nodal steps.

From Table 4.2.1, the discharge-area coefficient β_3 attempts to characterise the nature of the three storm events. This involved replacing the initial surface for the second storm event with the last generated surface from the first event. i.e. gully-0000060.rst2 is used as the initial surface file for the 010197 storm.

Upper Section

The extension of the batter slope study area to incorporate the 10m of the gully catchment is described in detail above. The expected equilibrium profile for the overall landscape (Figure 1.1.4) tends to indicate that incision of the high wall will extend back into the cap. By extending the profile of the slope to include this additional 10m, with a slope of 2%, this aspect will be investigated.

Alteration of input parameters was restricted to a revised initial surface profile only. However, due to the extensive erosion expected at the head of the gully (at the inlet points), it is possible that a similar landscape to the standard case will be generated, except that erosion will extend a further 10m.

This may indicate the runoff, drainage density being the dominant erosion factor, rather than the slope transition between the catchment and the batter site. Considerable amounts of water are applied to these upper sections, with the development of a gully on these slopes more closely resembling theoretical behaviour.

Random Erodibility

The erodibility of the rock material of the NWRD was approximated from calibration of the sediment transport equation parameter β_1 from previous studies and modified using the bulk density (Section 4.1) to represent the erosional characteristic of the batter slope.

The entire landform represents a diverse range of erodibility, a function of mean particle diameter, d_{50} and geophysical weathering characteristics of the material, by introducing a random multiplier to the β_1 parameter, a more dynamic and realistic behaviour may be achieved.

As described above, the operational parameter 'ModeRn' has been already implemented, with the coefficient multiplier involving the alteration of the initial surface profile file from a default value of 1.0. By generating a random distribution between 0 and 5, with a mean of 1.0, the overall characteristics of the site is unchanged, but variation in the erodibility of the material has been introduced.

This aspect incorporates a more realistic impression of the gully development observed on site, with pathway dictated primarily by the variability of the material, or the dominant runoff drainage density relationship.

The sediment transport relationship has 2 major components, one of which depends on discharge (relative directly to the amount of water feeding each node) and the other is dependent on slope.

As outlined above, it is expected that for the standard homogenous case the pathway of the gully adopted will not be significantly affected by the random perturbations given to the initial surface elevations. The pathway will more than likely be straight down the slope, depositing material at the change of curvature point between Row G to Row I, before the dominant erosional process changes to be a function of material erodibility. This will be reflected in the comparison between this simulation scenario in the standard batter profile and extended profile cases.

By incorporating random erodibility into this relationship, the pathway adopted will vary, and move across the slope for the standard profile, however once the gully is instigated it is considered unlikely that a new path could be commenced as the drainage density of each node within the gully increases dramatically once it has formed (Figure 4.3.1).

Another interesting consideration may be the effect of deposition on the gully pathway adopted. Although the batter slope was relatively uniform, and the development observed on site was dominated by the initial erodibility of material in the upper sections, deposited sections tended to influence the pathway adopted below the point of curvature change. By changing the behaviour of the simulated gully from a straight line (standard case) to a more realistic random motion, less material was concentrated at these points.

The drainage direction of the nodes surrounding each node point is illustrated in Figure 4.3.1 below, with this indicating which of the 8 adjacent nodes the current node drains into. Once the gully is established, this pathway seems to be determined by dominant drainage direction until the slope component driving the sediment transport equation is reduced in the lower sections.

Once the gully was initiated, the drainage density relationship remains dominant until slope component becomes considerable, observed in transition in lower sections with accumulated material.

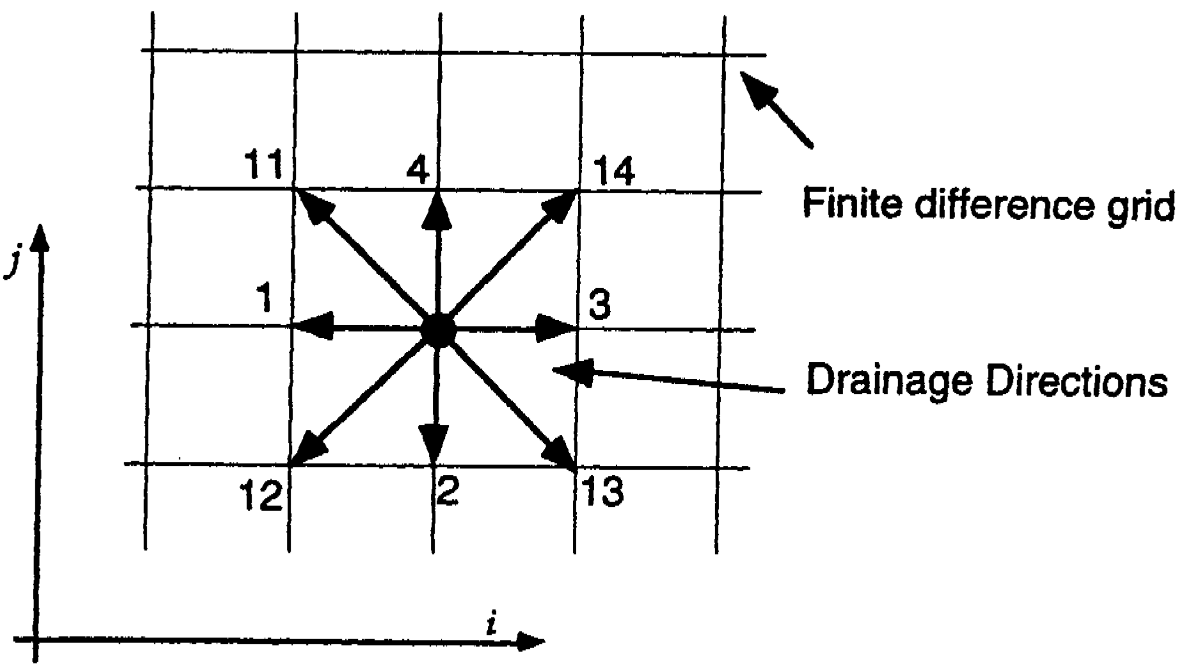

Figure 4.3.2: Drainage direction of the finite difference grid indicates which of the 8 adjacent nodes each node drains into (Willgoose, 1992 Figure 1). The drainage density of the gully once it has been initiated will tend to dictate only one pathway to be adopted. This may be overcome by increasing the grid discretisation of the profile, as well as widening the inlet point or introducing erodibility with depth relationship as described below.

Differential Erodibility with Depth

Armouring was considered to represent the decrease in erodibility with depth of erosion. Conceptually this model is an exponential relationship, a function of mean particle diameter, and represents the risk of erosion of the material at various depths into the batter slope.

The mean particle diameter, d_{50} was used as the measure of the change in the surface characteristic and was incorporated into the following relationship (Figure 4.3.2):

$$\text{erodibility} = \text{initial erodibility} * \frac{1}{C * \text{depth}^{\text{exponent}} + 1} \qquad (4.3.1)$$

where

depth = depth of erosion from commencement
exponent = exponent on the depth of erosion (set initially to 1)
C = coefficient reflects the initial and final mean grain size over a given depth eroded.

The implementation of this erosion module involved considerations such as the crude measure of the change in erodibility, no distinction between previous eroded material, and unsullied hillslopes, and conservative estimates of relationship parameters.

Conservative estimate of the erodibility of surface material is based on relationship: $1/d^{3/2}$, with d_{50} initial at 2mm = $1/2^{3/2}$ leading to erodibility ~ 1/3, whilst d_{50} final at 20mm at a depth of 2m = $1/20^{3/2}$ ~ 1/90 represents a reduction in erodibility by a factor of 1/30.

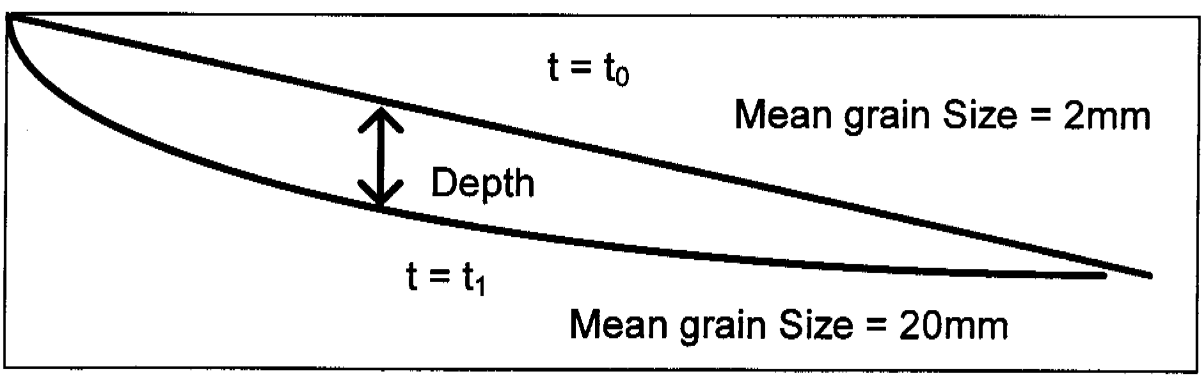

Figure 4.3.2: The effect of the change in d_{50} of surface material with depth represents the next component of the investigation. Although initial and final grain sizes were set to 2mm and 20mm respectively, they represent a conservative approximation.

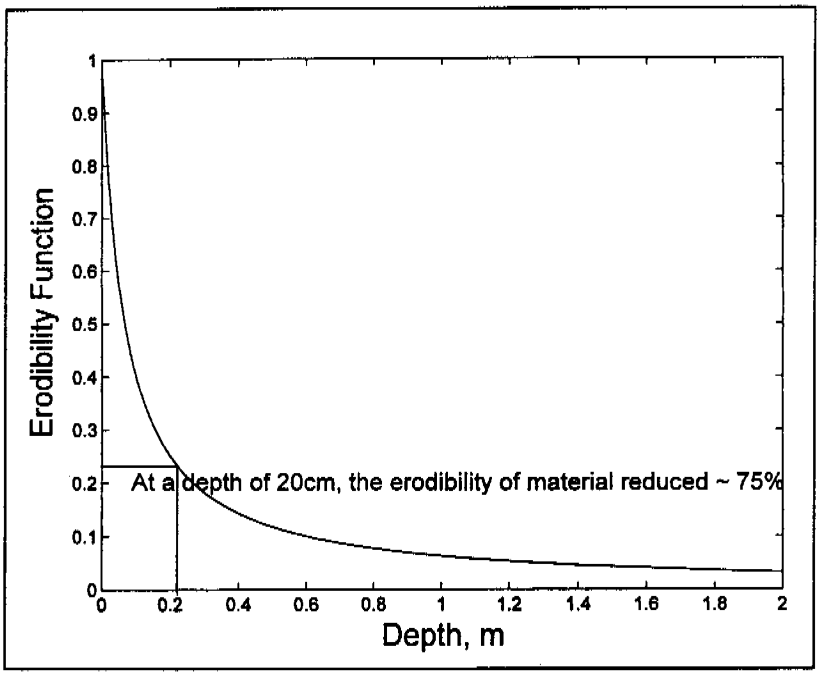

Figure 4.3.3: The change in erodibility function term (1/coefficent*depth^{exponent}+1) represents an exponential relationship between the depth and erodibility of the surface, determined from the coefficient (relating mean grain size, d_{50}) allocated (C ~ 2). i.e. at a depth of 20cm, the erodibility function is ~ 0.25 equating a reduction in erosion of 75%.

The erodibility of the surface, as the gully forms rapidly decreases with parameter values of C ~15, and C ~2 being considered. Although this is a relatively crude relationship applied to an extremely complex process, it represents a reasonable estimate or summary of the interaction observed on site, with a dramatic decrease in erodibility of the 'channel bed' once the fine material (d_{50} small) was removed leaving larger boulders exposed, Figure 4.3.4.

Incision in the upper section of the batter slope ranged between 40 and 80cm, with armouring maximised on the very upper sections where water velocity was minimal. Once this characteristic was in place, little further movement or activity occurred.

Further approximations in the erodibility-depth function included the evaluation of sections where deposition had occurred. These sections composed of the fine material from the upper sections represented a highly erodible surface (observed) and implementation of differential erosion between original hillslope and these components represent future research (pers. com. Willgoose, 97).

Numerous modelling scenarios were investigated during the experimental stage, with the impact of various components of the model assessed by progressive inclusion to

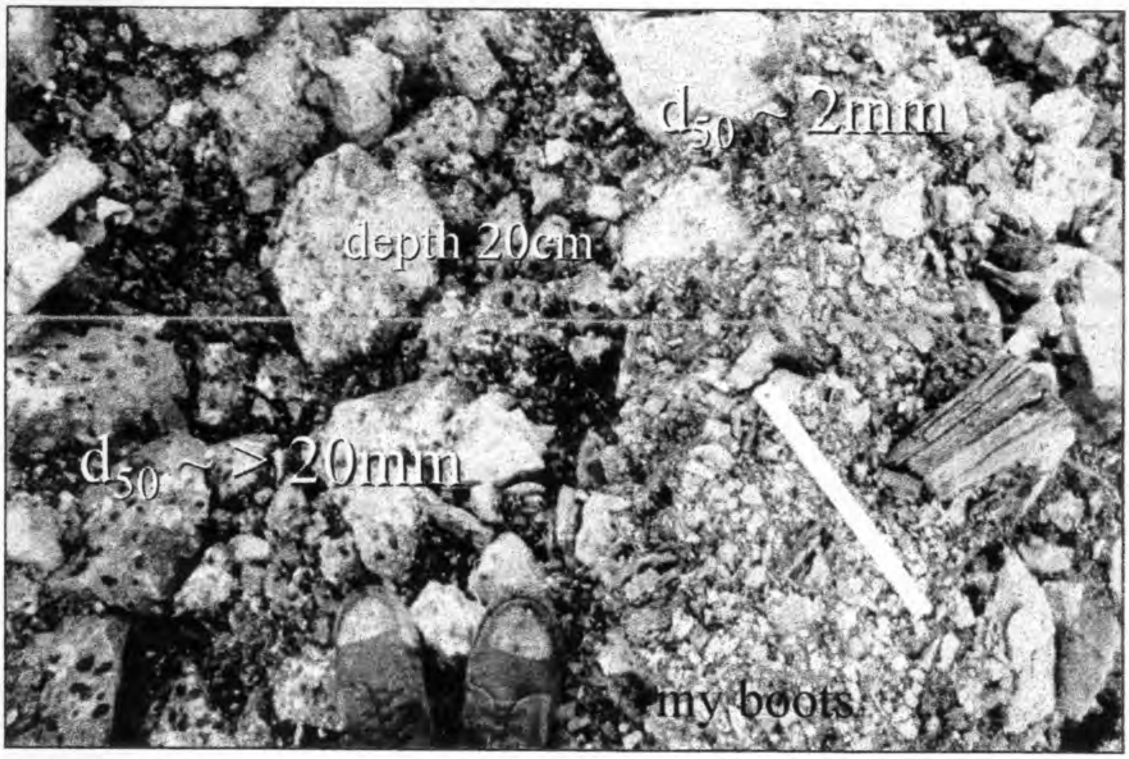

Figure 4.3.4: The difference observed in mean particle diameter, d_{50} between the active (gully) and inactive (hillslope) components of the surface was significant. The fine material observed was quickly eroded leaving large rock fragments exposed which significantly resisted further movement.

an eventual best possible representation. By comparison between the nature of the gully and predictions from the SIBERIA model, an understanding of the soil erosion mechanisms in operation on site can be developed.

Determination of impact of additional components such as heterogeneity, and armouring evolves the prediction to resemble the nature of the actual landform, as closely as possible. Feed back indicated areas of sensitivity, such as the exponent on the slope component in the sediment transport equation, and allowed the evaluation of gullies likely to be formed on the steep batter slopes.

From these regimes, the impact of each component can be assessed, with the final scenario representing the combination of all the erosional mechanisms.

A series of scenarios were considered in this methodology:

- assessment of the behaviour of the exponent on the slope component n_l with both the standard and extended profile batter sites.

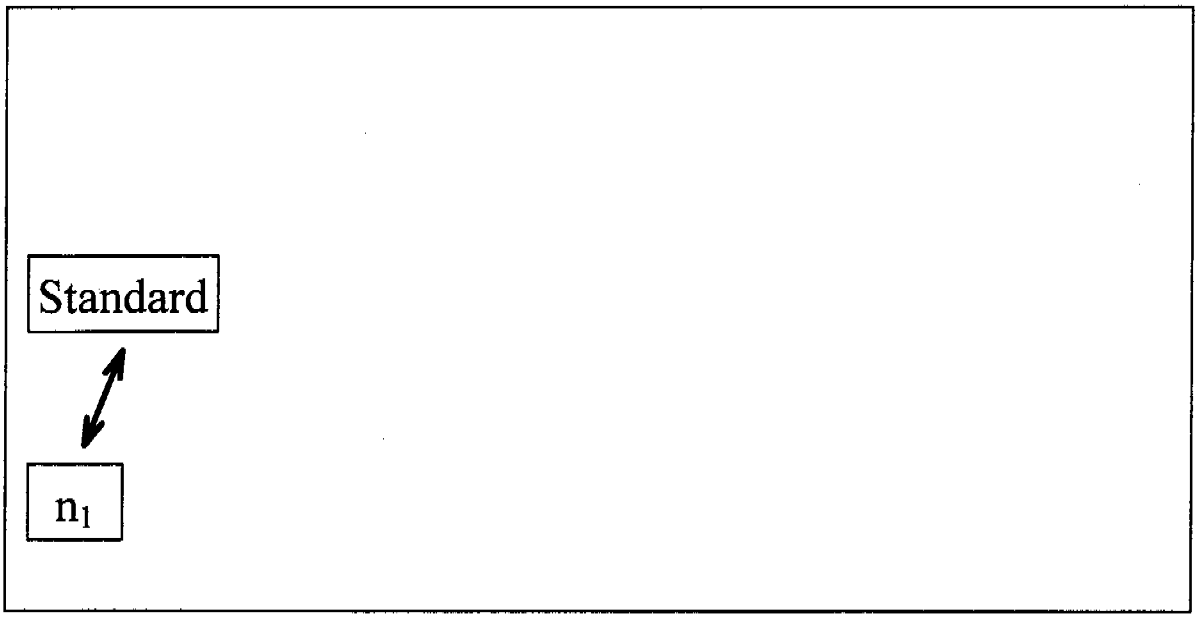

Figure 4.3.5: Two case scenarios were run; standard refers to the assumption of homogenous material, with armouring module disable, and the inclusion of extended profile in the second file.

```
SIBERIA      8.01
    60      10      20      70       0       0
     5       1       0       1       0       2
     0       0       1       0       0       0
     0       0
  0.000000   1.000000   0.000000   0.000000   1.000000
  1.000000   0.000000   1.000000   0.100000   0.000000
  0.000000   0.000000   0.000000   0.000000   0.005000
  1.000000   1.000000   0.002720   0.112000   1.680000
  0.690000   1.930000   0.100000   2.500000   0.300000
 10.000000   0.400000   0.100000   2.000000   1.000000
  0.000000   1.000000   1.000000   1.000000   0.000000
  0.000000   0.000000   0.000000   0.000000   0.000000
  0.000000   0.000000   0.000000   0.000000   0.000000
  0.000000   0.000000   0.000000   0.000000   0.000000

fup.dat

 4
 8 2
 9 2
 10 2
 11 2
.0000E+00 1.0000 0.0010 0.1771374E+00    0  5 0.0000E+00 0.0000E+00
```

Upper Surface with n_l at 0.69, non-armouring, homogenous.

n_l at 0.69, and upper inlet runoff module

Figure 4.3.6: These are the parameter files used to generate the standard and extended profile batters, with exponent on the slope component n_l changed from 2.1 to 0.69, equation 4.1.9.

- assessment of increasing the inlet width from 2 node points for narrow case, to 4 inlet points for the wide case.

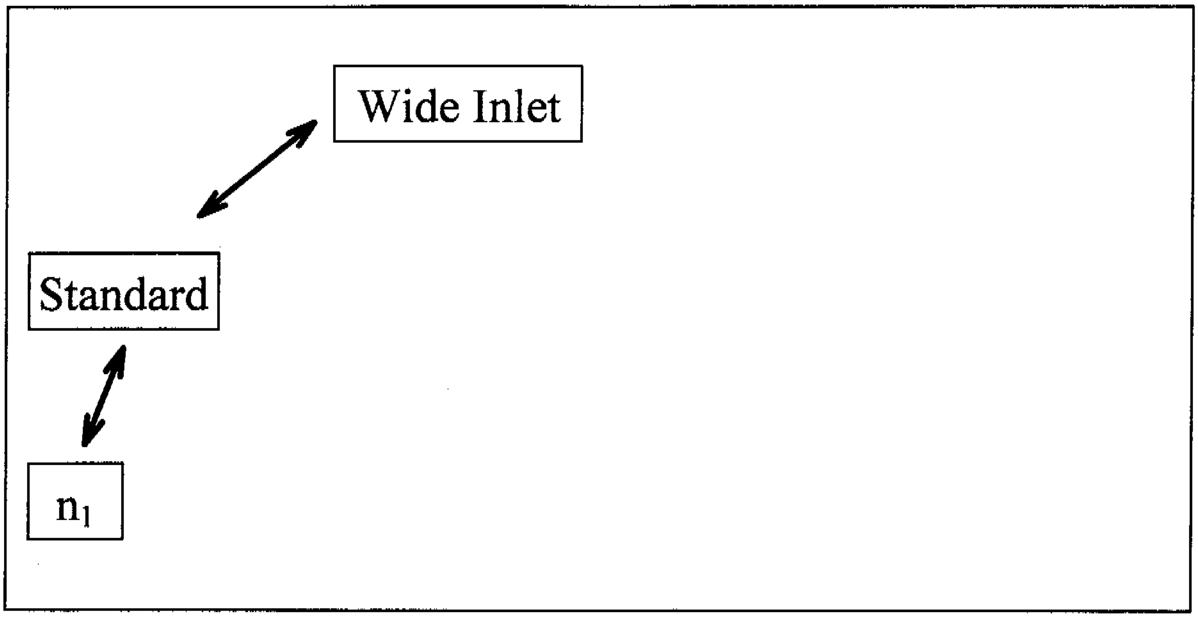

Figure 4.3.7: Parameter files incorporating wide inlet points, and alteration of the user defined runoff module file to describe either the narrow or the wide case.

The parameter files used in these scenario are as follows:

```
SIBERIA      8.01
   60     10     20     60      0      0
    5      1      0      1      0      2
    0      0      1      0      0      0
    0      0
   0.000000    1.000000    0.000000    0.000000    1.000000
   1.000000    0.000000    1.000000    0.100000    0.000000
   0.000000    0.000000    0.000000    0.000000    0.005000
   1.000000    1.000000    0.002720    0.112000    1.680000
   2.100000    1.930000    0.010000    2.500000    0.300000
  10.000000    0.400000    0.100000    2.000000    1.000000
   0.000000    1.000000    1.000000    1.000000    0.000000
   0.000000    0.000000    0.000000    0.000000    0.000000
   0.000000    0.000000    0.000000    0.000000    0.000000
   0.000000    0.000000    0.000000    0.000000    0.000000

fwide.dat
          <------    wide inlet runoff module

 4
 8 2
 9 2
 10 2
 11 2
.0000E+00 1.0000 0.0010 0.1150964E+00    0  5 0.0000E+00 0.0000E+00
```

Figure 4.3.8: The implementation of this simulation involved altering the user defined runoff module to represent a more evenly distributed inlet flow. This file standard profile, with wide inlet point.

- assessment of the alteration of the random field multiplier parameter was used to introduce heterogeneity. Another two scenarios were also used to compare the combined of both the wide inlet feed along with randomised erodibility.

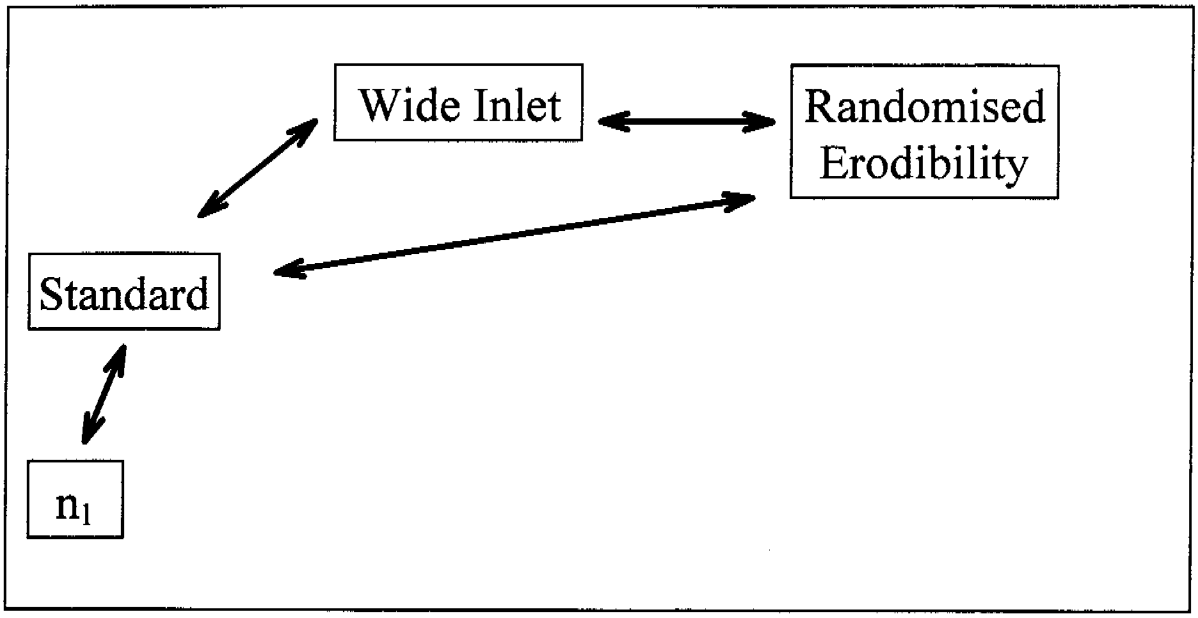

Figure 4.3.9: Methodology flow-paths for the inclusion of wide inlet point, and introduction of randomised erodibility to the batter slope material.

The parameter files used in these scenario are as follows:

```
SIBERIA      8.01
   60     10     20     60     0     0
    5      1      0      1     0     2
    0      0      1      0     0     0
    0      0
  0.000000    1.000000    0.000000    0.000000    1.000000
  1.000000    0.000000    1.000000    0.100000    0.000000
  0.000000    0.000000    0.000000    0.000000    0.005000
  1.000000    1.000000    0.001990    0.112000    1.680000
  2.100000    1.930000    0.010000    2.500000    0.300000
 10.000000    0.400000    0.100000    2.000000    1.000000
  0.000000    1.000000    1.000000    1.000000    0.000000
  0.000000    0.000000    0.000000    0.000000    0.000000
  0.000000    0.000000    0.000000    0.000000    0.000000
  0.000000    0.000000    0.000000    0.000000    0.000000

f.dat

 4
 8 2
 9 2
 10 2
 11 2
.0000E+00 0.1119 0.0010 0.5261294E-01    0  5 0.0000E+00 0.0000E+00
```

Second storm event, $\beta_3 = 0.00199$

Change in random field multiplier

Figure 4.3.10: The implementation of this simulation involved altering integer parameter ModeRn, and adjusting the multiplier coefficients in the initial landscape file, along with increasing inlet width.

- assessment of depth-erodibility relationship, equation 4.3.1 was used to determine the reduction factor that was multiplied by the erosion depth evaluated by SIBERIA before the new elevations for the batter slope catchment were calculated.

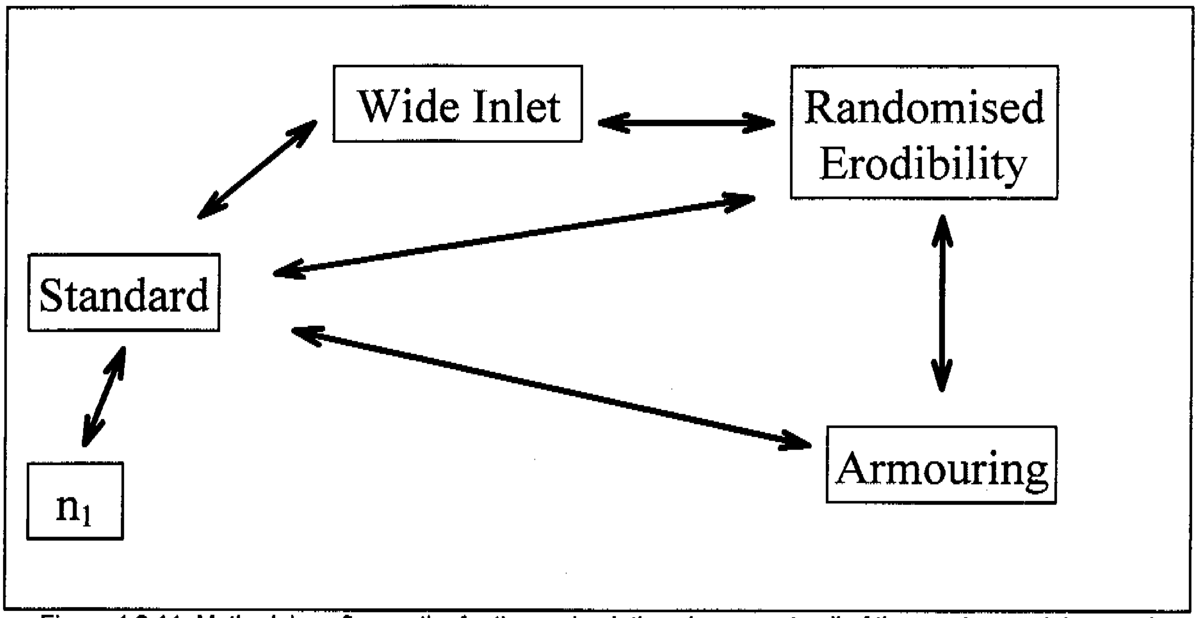

Figure 4.3.11: Methodology flow-paths for these simulations incorporate all of the erosion modules used in this study.

The parameter files used in these scenario are as follows:

```
SIBERIA     8.01
    60      10      20      70      0       0
     5       1       0       1      1       2
     0       0       1       0      0       0
     0       0
    0.000000   1.000000   0.000000   0.000000   1.000000
    1.000000   0.000000   1.000000   0.100000   0.000000
    0.000000   0.000000   0.000000   0.000000   0.005000
    1.000000   1.000000   0.002720   0.112000   1.680000
    2.100000   1.930000   0.100000   2.500000   0.300000
   10.000000   0.400000   0.100000   2.000000   1.000000
    0.000000   1.000000   1.000000   1.000000   0.000000
    0.000000   0.000000   0.000000   0.000000   0.000000
    0.000000   0.000000   0.000000   0.000000   0.000000
    0.000000   0.000000   0.000000   0.000000   0.000000
armour.dat
fup.dat
```

Armouring module

Random multiplier factor not altered between simulations.

```
 4
 8 2
 9 2
 10 2
 11 2
.0000E+00 0.0379 0.0010 0.5501554E-01    0  5 0.0000E+00 0.0000E+00
```

Figure 4.3.12: The implementation of this simulation incorporated the user defined sediment transport rate 'armour.dat'. Incorporates extended profile, randomised erodibility, and differential erode with depth

- investigation into the sensitivity of the exponent on the slope component of the sediment transport equation, n_l constituted the final step in the modelling analysis.

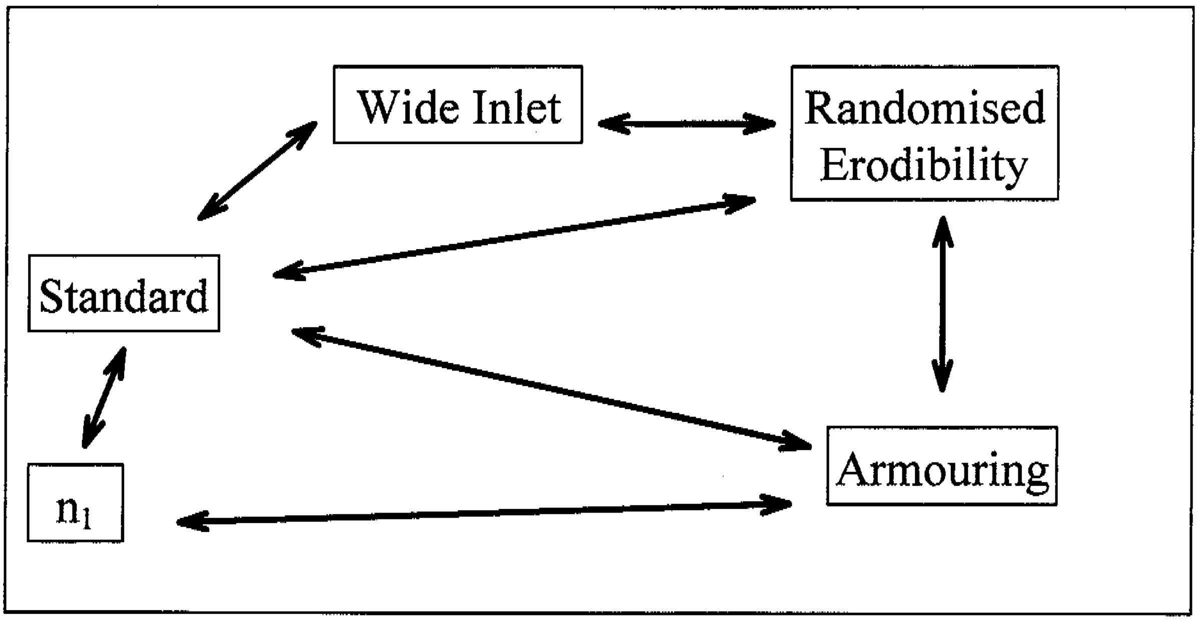

Figure 4.3.12: Methodology flowpaths for these simulations incorporate all of the erosion modules used in this study, combined with a exponent on the slope parameter, n_1 = 0.69 in place of 2.1.

The parameter files used in these scenario are as follows:

```
SIBERIA      8.01
     60     10     20     70      0      0
      5      1      0      1      1      2
      0      0      1      0      0      0
      0      0
     0.000000    1.000000    0.000000    0.000000    1.000000
     1.000000    0.000000    1.000000    0.100000    0.000000
     0.000000    0.000000    0.000000    0.000000    0.005000
     1.000000    1.000000    0.002720    0.112000    1.680000
     2.100000    1.930000    0.100000    2.500000    0.300000
    10.000000    0.400000    0.100000    2.000000    1.000000
     0.000000    1.000000    1.000000    1.000000    0.000000
     0.000000    0.000000    0.000000    0.000000    0.000000
     0.000000    0.000000    0.000000    0.000000    0.000000
     0.000000    0.000000    0.000000    0.000000    0.000000
armour.dat
fwideup.dat









  4
  8 2
  9 2
  10 2
  11 2
.0000E+00 0.0379 0.0010 0.5501554E-01     0  5 0.0000E+00 0.0000E+00
```

Figure 4.3.13: This simulation investigates the sensitivity of the slope exponent n_1 with all of the erosion modules enabled. This file incorporates all of the modelling components of randomised erodibility, armouring, and extended profile with wide inlet field, and n_1 = 0.69.