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Development of an integrated model for water induced top soil erosion and shallow landslides

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Abstract: Rainfall induced soil erosion and shallow landslides are the main sources of sediment supply in hilly catchments. These processes are generally modelled separately; erosion models are used to predict soil loss and landslide models are used to assess slope failures and mass movements. However, an integrated model is desirable because it would permit the chronological simulation of pre-failure sediment yield, the prediction of landslide occurrences, and post-failure sediment yield. This paper reports on the development and application of a preliminary and simple methodology for integrating the Water Erosion Prediction Project (WEPP) model with an infinite slope method of slope stability analysis.

The integrated soil erosion and shallow landslide model functions within a GIS platform where topography, soils, climate, and land management data are the model's main inputs. Pre-failure catchment scale sediment yields are simulated by the GeoWEPP model using both the flowpath and representative hillslope methods. Soil moisture at various points within the catchment is then determined from WEPP hillslope profile simulations. The soil moisture values are then combined with soil depth and porosity to compute a soil wetness index at each of these points. A soil wetness index raster map is then created by interpolating the point map and used as an input for a slope stability model. Landslide probability values are determined for each grid cell within the catchment.

The methodology was applied to a 300 ha catchment in New Zealand with slopes ranging from about 1 to 40°. All required GIS datasets were prepared in a 10 m grid resolution. The DEM was built from a LIDAR dataset. Soil data was obtained from a 1:15,000 scale soil map of the catchment and laboratory analysis of geotechnical and chemical properties of soil samples collected from 30 different locations within the catchment. The land cover map was digitized from a 1 m grid resolution aerial photograph. Daily rainfall data were obtained from an automatic rainfall station located inside the catchment. Other climatic data such as radiation, temperature and wind direction were collected from a climatic station located 4 km north of the study area.

Sediment yields and the locations of probable landslides within the catchment were obtained by the application of the integrated model. Model simulations with the catchment's highly erodible soils resulted in an average sediment yield of about 9 T ha^{-1}. Also as expected, soil moisture and wetness indices were higher in downslope areas of the catchment resulting in high landslide potentials in those regions. The model produced a total of 19 spatially distributed potential landslide locations occurring on pasture land. Seven of those were actually identified in the field through surveying and aerial photograph interpretation.

The integrated modelling approach for simulating soil erosion and shallow landslides is a significant improvement over the traditional steady state sub-surface hydrological models used in stability models; however further calibration and validation of the model is needed. Research is also underway to improve soil wetness index simulations for all cells within the catchment by using total soil water content derived from the WEPP flowpath method. Finally, modelling tools are being developed to help predict long term changes in sediment yields after landslides due to changes in topography.

Keywords: *Surface erosion, soil wetness index, shallow landslides, GIS modelling*

1. INTRODUCTION

Water induced shallow landslides and top soil erosion are common hydrological processes in hilly and mountainous catchments. These processes are generally studied separately; erosion models are used to predict soil loss and landslide models are used to assess slope failures and mass movements. Erosion models can either be empirically based such as the Universal Soil Loss Equation (USLE), conceptually based like the Agricultural Non-Point Source Pollution Model, or physically based such as the Water Erosion Prediction Project (WEPP). Landslide investigations are generally carried out using landslide inventories, statistical analysis, or by physically based approaches. The infinite slope method of slope stability analysis is one of the most widely adopted physically based approaches in shallow landslide assessment.

The independent application of erosion or landslide models is useful for land management; however, limitations arise from the fact that each of these models simulates or uses its own baseline hydrology and water balances. Soil moisture, for example, is a key parameter for both erosion and landslide models. If soil moisture is predicted differently for an erosion model than for a landslide model, the magnitude of erosion and landslide results may differ. It was therefore hypothesised that developing a model which would share basic hydrology would result in an integrated and improved prediction of erosion and landslides.

The main objective of this paper is therefore to report on the initial development of an integrated soil erosion and shallow landslide model where:

- WEPP is used to predict both erosion and soil moisture within a catchment.
- WEPP predictions of soil moisture are used to calculate a soil wetness index for a landslide model to assess the water induced shallow landslide potential in a catchment.

The methodology is demonstrated using a research catchment in New Zealand (Bowenvale Reserve, Christchurch).

2 MATERIALS AND METHODS

2.1 Selection of WEPP and a shallow landslide model

WEPP (Flanagan and Nearing, 1995) was chosen as the base model for the integrated erosion and landslide modelling approach because it is a well recognized physically based erosion model that simulates overland and channel flow routing needed for sediment transport, as well as subsurface flows and total soil water content. WEPP can be described as a continuous simulation model that can predict spatial and temporal distribution of net soil erosion and deposition within a hillslope or catchment. WEPP has various components that simulate surface and subsurface hydrology, irrigation, water balance, plant growth, residue decomposition, winter hydrology, and overland-flow hydraulics.

Daily or single-storm climate data may be used in WEPP. Runoff in the model is simulated as the difference between effective rainfall and infiltration rate, and is routed over the land surface on the basis of the kinematic wave equation. Infiltration is computed using the Green-Ampt Mein Larson model modified for unsteady rainfall. In the simulation process, rainfall interception by canopy, storage due to surface depression, deep percolation and subsurface flow are also considered. Daily total soil water content is simulated using a water balance equation that incorporates infiltration, runoff routing, soil evaporation, plant transpiration, snow melt and seepage. Subsurface simulation is based on equations proposed by Sloan and Moore (1984). Hillslope erosion is estimated as interrill (sheet) and rill (i.e. micro channel) erosion; the former is treated as soil detachment by raindrop impact and subsequent sediment delivery to rills, and the latter is a function of sediment detachment due to excess flow shear stress and transport capacity of concentrated flow as well as the sediment load already in the flow. When the transport capacity of sediment within a rill is exceeded due to changes in slope or flow, deposition occurs.

The WEPP model can be applied to a single hillslope profile or to a small catchment. A hillslope can be divided into multiple overland flow elements (OFEs) to incorporate the spatial distribution of soil and vegetation type. Soil and vegetation characteristics in each OFE are unique and uniform. To apply the WEPP model to a catchment, the catchment must be discretized into hillslopes and channel segments or into flowpaths. The detail procedures of catchment descritization, identifying representative hillslopes, channels, and defining flowpaths are described in Cochrane and Flanagan (2003). To automate this discretization, GIS based tools have been developed (Cochrane and Flanagan, 1999; Renschler, 2003). In GIS, flowpaths are defined as the topographical routing of water from one cell to the next starting from a cell having no water flowing into it and eventually discharging into a channel. For the hillslope method, a representative topographical profile is derived by averaging topography of all individual flowpaths of that hillslope and applying WEPP to that profile. The flowpath method on the other hand, consists of applying WEPP to all possible flowpaths in each hillslope. The flowpath method predicts the soil detachment and deposition rate in each cell.

The infinite slope method of slope stability analysis is a widely accepted tool to assess water induced shallow landslides in mountainous and hilly catchments because their topographic surface is quite often underlain by a bedrock plane lying parallel to the slope. The potential failure depth generally lies at a depth below the surface which is small compared to the length of the slope. The infinite slope method determines the slope stability factor i.e. safety factor of the slope which expresses the ratio of stabilizing to destabilizing forces. Digital data, such as the spatial distribution of soil types, land-use, vegetation and digital elevation model (DEM) are used to determine the safety factor (F.) In this study, F is calculated with a method adopted by Van Western and Terlien (1996) as presented in Eq. (1) and (2).

$$F = \frac{C_s + C_r}{D\gamma_e \sin\alpha} + \left[1 - m\frac{\gamma_w}{\gamma_e}\right]\frac{\tan\varphi}{\tan\alpha} \qquad \text{Equation 1}$$

where F is the safety factor (-), C_s and C_r are the soil and root cohesion (N m^{-2}) influenced by soil and vegetation types respectively, D is the thickness of overlying soil (m), φ is the angle of internal friction (-), α is the local slope angle γ_w is the unit weight of water (N m^{-3}) and γ_e is the effective unit weight of the soil and is given by

$$\gamma_e = \frac{q\cos\alpha}{D} + m\gamma_s + (1-m)\gamma_d \qquad \text{Equation 2}$$

where γ_d is the dry unit weight (N m^{-3}), γ_s is the saturated unit weight (N m^{-3}) of the soil, q is the surcharge (N m^{-2}) on the soil surface. The term *m* in both equations is the soil wetness index (-) which is the relative saturated depth (thickness of saturated zone divided by total soil thickness) (Burton and Bathurst, 1998). Every term except m in Eq. (1) and (2) is space variable, however, the soil wetness index (m) also varies with time and depends on the hydrological processes in the hillslopes. The value of m ranges from 0 to 1; 0 for completely dry soil and 1 for saturated soil. The total soil water simulated by the WEPP model is used in the landslide model to quantify the soil wetness index for each cell. The criterion to decide whether a slope is stable or unstable depends upon the value of F being larger or smaller than 1. Montgomery and Dietrich (1994) define four stability classes depending upon the influence of the soil wetness: unconditionally unstable if the slope is unstable even when dry or when the safety factor is smaller than 1; stable if F is larger than 1.5 even when the soil is fully saturated, and two other classes defined between F = 1 and 1.5 (Table 2).

Table 2: Stability classes according to the safety factor value

Safety factor	Slope stability	Remarks
F > 1.5	Stable	Only major destabilizing factors lead to instability
1.25 < F < 1.5	Moderately stable	Moderate destabilizing factors lead to instability
1 < F < 1.25	Quasi-stable	Minor destabilizing factors can lead to instability
F < 1	Unstable	Stabilizing factors are needed for stability

The integrated modelling procedure adopted for this study uses WEPP and the landslide model as shown in Fig. 1. This procedure is described in greater detail through its application to the Bowenvale research catchment in New Zealand.

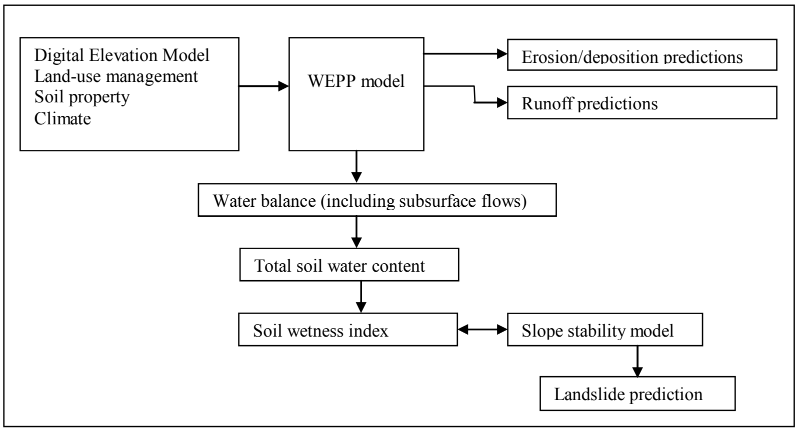

Figure 1: Modelling flowchart for top soil erosion, runoff, and shallow landslide predictions.

2.2 Study Area and model application

Study area:

The Bowenvale Reserve Catchment (43°34′58"S and 172°38′27"E to 43°36′20"S and 172°39′45"E), which is south of downtown Christchurch, New Zealand, was used as an example application of the integrated erosion/landslide model (Fig. 2A). The reserve covers an area of approximately 300 ha. and serves as a tourist and recreational destination. A 10 m grid cell size resolution Digital Elevation Model (DEM) of the study area was developed from a LIDAR dataset. The catchment elevation ranges from about 19 to 492 m above the mean sea level (Fig. 2B) and the slope varies from about 1 to 40° averaging about 22°.

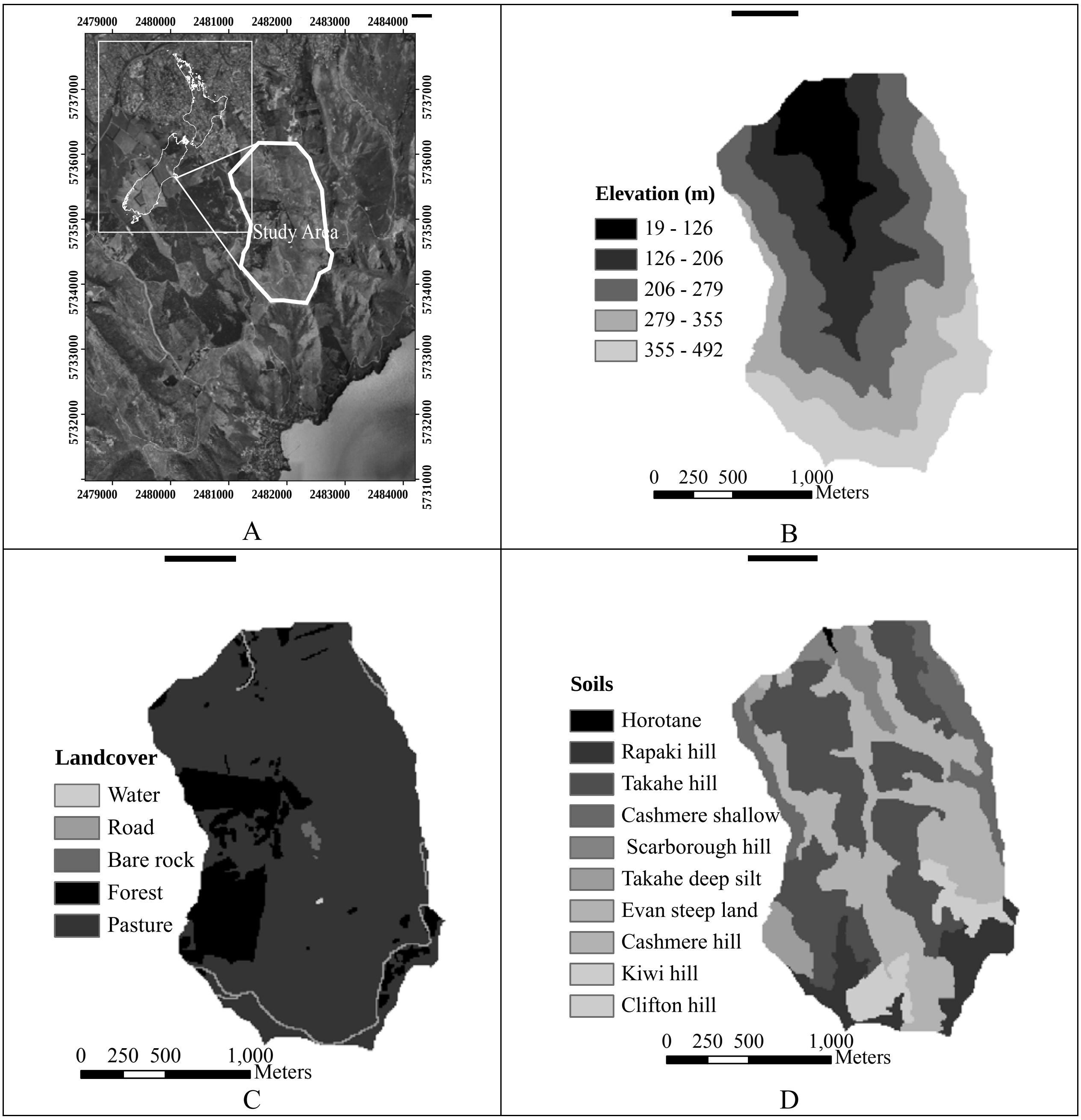

Figure 2: Bowenvale Catchment (A) Location, (B) Digital Elevation Model, (C) Land-use pattern, and (D) Soil types

Digital data of land-use patterns of the study area were developed by digitizing land-use features from high resolution aerial photographs and field verified with a GPS. The study area was divided into five main types of land cover (Fig. 2C). Forest and pasture land are the main land-use types and they account to more than 98% of the catchment. The forest area includes exotic plantations of mostly conifers, Eucalyptus trees, and native forests.

The study area's soil data (Fig. 2D) was generated from a 1:15,000 soil map (Trangmar, 1998). Soil is shallow and rock outcrops can be seen in different parts of the catchment. The study area has 10 well defined soil types consisting of mainly loess. Takahe Hill and Evan Steep Land Soils (sandy loam soils) are the main soil types which respectively cover about 35% and 23% of the total area. Soil properties were gathered from the existing soil database (Trangmar, 1998), laboratory analysis of the collected soil samples and from field investigations. The database provides the information on soil's texture, parent materials, drainage condition and depth. The soils' physical and chemical properties were obtained from laboratory tests conducted on 30 different samples across the catchment (2 to 5 samples per mapped soil type). These soil properties are assumed to be uniform within each soil type. Soil's erodobility parameters such as interrill erodibility, critical shear stress and rill erodibility were computed internally in WEPP.

Geo-technical properties of the soils, such as angle of internal friction and cohesion, were derived from four direct shear tests on samples collected at 40-50 cm depths. Dry and saturated densities for each soil type were obtained from the literature according to the soil textures. Root cohesion and surcharge were derived from the land cover map using values given in literature for similar land covers.

Historical (1989 -2008) daily rainfall data collected from an automated rainfall station in the catchment show that annual rainfall in the catchment ranged from about 435 mm in 2001 to 1040 mm in 2006, averaging about 750 mm yr^{-1}. The highest daily rainfall for the 1989 to 2008 period recorded was of 122.6 mm on 28 August, 1992 were the annual rainfall totalled 977.6mm. Other climatic data such as radiation, temperature and wind direction were collected from a station located, 4 km north from the study area. The exposed north western slopes of the catchment are subject to the full force of the dry north-west winds in summer, while the eastern slopes are exposed to the cooler drying north easterly winds. Temperature reductions with increase in altitude are not significant. Mean January air temperatures ranges from 16˚C at lower altitudes to 13.5˚C at higher altitudes

Model Application:

For WEPP modelling purpose, the catchment was discretized into channels and hillslopes which best represented actual conditions. A total of 33 hillslopes were generated and the areas of each hillslope varied from about 2 to 25 ha. Initial erosion modelling was done using GeoWEPP which provides a GIS based WEPP interface (Renschler, 2003). The model was run using both the representative hillslope and flowpath methods.

Since GeoWEPP does not have an automatic way of producing soil moisture output maps from WEPP simulations, soil moisture values were obtained from individual WEPP hillslope simulations. For each of the 33 hillslopes in the catchment, soil moisture results from at least three hillslope profiles were obtained by using a user defined selecting tool (Cochrane and Flanagan, 2003). Soil moisture was computed for approximately 600 OFEs of 122 user selected hillslope profiles. The soil moisture values were then combined with soil depth and porosity to compute a soil wetness index at each of these points. A soil wetness index raster map was then created by interpolating the point map and then used in the slope stability model. Landslide probability (safety factor) values were then determined for each grid cell within the catchment.

Landslides within the catchment were mapped from GPS based field surveys and from the analysis of the aerial photographs. Comparisons on the spatial distribution of actual and modelled landslides were done.

3 RESULTS AND DISCUSSION

Erosion simulations from both the hillslope and flowpath methods resulted in high sediment yields due to highly erodable soils (fine sands and silt) present in the catchment. Overall, the hillslope method produced higher sediment yields than the flowpath method. Erosion from the hillslope method is calculated for a single representative topographical profile where topography, land management and soil data in the hillslope are averaged, virtually eliminating deposition zones. The detachment and deposition rates from the flowpath method, on the other hand are simulated for each cell based on WEPP simulations along all possible flowpaths in the catchment. GeoWEPP identified 2481 flowpaths in the study area. With the flowpath method, about 45% of the study area has high annual detachment rates (greater than 4 t ha-1) as seen in Fig. 3A. These high rates predominantly occur along slopes steeper than 20°. Pasture land encompasses about 90% of high erosion areas and the rest are in the forested areas.

As expected, the WEPP simulated total soil water in the catchment peaked on August 28, 1992, when the daily rainfall was the highest (122.6 mm). The spatial distributions of soil wetness index depicted in Fig. 3B shows that the values for that day range from 0.56 to 0.98 (close to fully saturated environment). The simulated indices were highly dependent on soil's hydraulic properties and depth; however subsurface flows also influenced their spatial distribution. Since the WEPP subsurface flow simulation is done using Sloan and Moore (1984) formula, higher values of wetness indices are readily observed in the downstream reaches of the hillslopes. However, more OFEs are required in a hillslope to better represent the spatial variability of total soil water content in a hillslope because total soil water content is simulated as a unique value for each OFE i.e. its spatial variability within the OFE is not considered in the simulation processes.

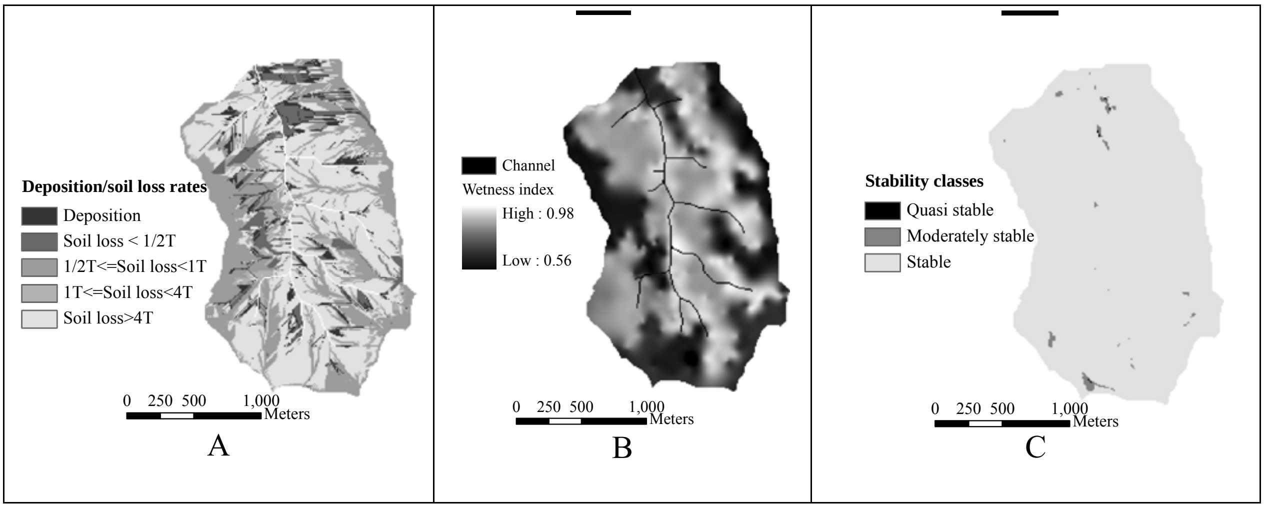

Figure 3: Spatial distribution of (A) deposition and soil loss rates, (B) soil wetness index, and (C) stability classes

The landslide modelling shows that none of the catchment is unconditionally unstable (safety factor less than 1) and that about 99% is unconditionally stable (safety factors greater than 1.5). About 1% of the catchment is in a quasi and moderately stable state. These are mapped in 19 different locations of potential landslide zones (Fig. 3C) and they all occurred within the pasture land-use type. The spatial distribution of potential landslide zones was controlled by topography, soil moisture and vegetation patterns. The modelled landslide distributions were compared with actual ones identified through aerial photographs and field surveys. Out of the 19 modelled potential landslide zones (quasi and moderately stable), seven of them match actual landslides. All potential landslide zones fall in areas that also have high detachment rates.

4 CONCLUSIONS AND FUTURE RESEARCH

An integrated modelling approach was developed for simulating water induced soil erosion and shallow landslides. The WEPP model was used to predict soil erosion and soil moisture. Predicted soil moisture values fed into a slope stability model. The advantages of this integrated modelling approach are that both the erosion and landslide model share the same hydrology, which is calculated continuously and includes factors such as vegetation growth, subsurface flows, and others. Apart from detailed erosion simulation, it also enables improved landslide modelling,

The continuous modelling with WEPP enables predictions of stability over time as soil moisture levels fluctuate due to rainfall, vegetation growth, and other parameters. This in turn will enable an improved prediction of when landslides may occur, and subsequently permit a better prediction of post-failure sediment yields.

The following research is underway to further improve and upgrade the model:

- Simulating total soil water content in each cell using the flowpath method,
- Add a soil mass redistribution model to predict the trajectories of the failed slope materials within the catchment and use this to simulate post failure sediment yields,
- Validate and calibrate the erosion/landslide model with time series stream discharge and sediment yield data from the Bowenvale catchment.

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