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**Sediment transport in forested head water catchments – calibration and
validation of a soil erosion and Landscape Evolution Model**

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Abstract

Sediment transport and soil erosion can be determined by a variety of field and modelling approaches. Computer based soil erosion and landscape evolution models (LEMs) offer the potential to be reliable assessment and prediction tools. An advantage of such models is that they provide both erosion and deposition patterns as well as total catchment sediment output. However, before use, like all models they require calibration and validation. In recent years LEMs have been used for a variety of both natural and disturbed landscape assessment. However, these models have not been evaluated for their reliability in steep forested catchments. Here, the SIBERIA LEM is calibrated and evaluated for its reliability for two steep forested catchments in south-eastern Australia. The model is independently calibrated using two methods. Firstly, hydrology and sediment transport parameters are inferred from catchment geomorphology and soil properties and secondly from catchment sediment transport and discharge data. The results demonstrate that both calibration methods provide similar parameters and reliable modelled sediment transport output. A sensitivity study of the input parameters demonstrates the model's sensitivity to correct parameterisation and also how the model could be used to assess potential timber harvesting as well as the removal of vegetation by fire.

Keywords: SIBERIA, sediment transport, forest hydrology, landscape evolution model, suspended sediment, bedload

1 Introduction

Sediment transport in forested catchments has been extensively studied using a range of both field (weirs, suspended sediment sampling and turbidity probes) and hillslope modelling approaches such as the RUSLE (e.g. Wischmeier and Smith, 1978; Webb et al., 1995; Evans, 2000; Cornish, 2001; Croke and Nethery, 2006; Webb et al., 2012a; b; Webb and Jarrett, 2013; Jamshidi et al., 2013; Nam et al., 2016) and WEPP (Elliot et al. 2001; Elliot, 2004; Rhee et al., 2004; Wade et al., 2012). In many areas of the world guidelines for erosion minimisation have been developed for steep slopes and forest harvesting (Hazelton and Murphy, 2007). However, the ability to model sediment transport in forests at the larger catchment scale has been not so well examined due to the paucity of long-term hydrology and sediment transport data. In particular, landscape evolution models (LEMs) (the focus here) have not been employed in this environment as yet.

Management of forested catchments is important as they provide a range of economic, social and environmental services (Webb, 2012). The site examined here (south-east Australia) provides for multiple uses, including timber for commercial harvest. Many forested areas are located in the headwaters of river systems, have relatively steep slopes and have not been cleared for other land uses (such as agriculture) due to their relatively shallow and poor quality soils. These steep catchments, due to orographic influence often have relatively high rainfall. This combined with their steepness can result in a relatively high erosion potential. The erosion potential increases when timber is harvested and therefore erosion mitigation practices need to be employed (Hazelton and Murphy, 2007).

It is important that we have the assessment and predictive capability to quantify hydrology and sediment transport for both natural and disturbed landscape systems, with the focus here on forested systems. There are many LEMs available all with different capabilities

and design focus (Coulthard, 2001; Tucker and Hancock, 2010). In this study we employ the SIBERIA LEM. SIBERIA is one of the most widely used and tested models for both short and long-term soil erosion and landscape evolution assessments. The advantage of using a LEM is that they operate using a Digital Elevation Model (DEM) of the catchment and erosion and deposition is calculated on a grid cell by grid cell basis (a common process of all LEMs). They all operate over different spatial (sub metre to tens of metres grid scales) and temporal (minutes to decades) scales. The most advanced models can operate at the minute time scales and employ DEMs at 0.1-0.2 m grid scale (Coulthard et al., 2012). LEMs offer potential to be employed for a range of landscape and catchment systems from post-mining landscapes to the steep forested areas examined here. LEMs allow erosion and deposition to be calculated on a catchment wide basis. Here we test the SIBERIA LEM for its ability to predict sediment transport in two relatively undisturbed catchments in New South Wales, south eastern Australia. A background and review of model history and framework can be found in Tucker and Hancock (2010).

While SIBERIA has been extensively tested at the small plot and hillslope scale (Hancock et al., 2000; Martinez et al., 2009; Hancock et al., 2007; 2011), these previous studies have all been focussed on agricultural catchments in either relatively low rainfall (~550 mm/yr) or tropical monsoonal environments (~1400 mm/yr). For all these studies, the model has been evaluated against decadal scale erosion rate data based on environmental tracers such as ^{137}Cs (Hancock et al., 2008) or compared with other models (Martinez et al., 2009). Importantly, there has been no direct comparison of the SIBERIA model against multi-year catchment scale sediment transport data.

A significant issue with the use of LEMs is their calibration and also validation of their output (Willgoose, 2005). There is a paucity of multi-year catchment scale sediment transport data (i.e. total sediment load) to calibrate and validate LEMs. If LEMs are expected

to operate at centennial to millennial time scales, then they should be able to be calibrated and predict accurate and reliable erosion rates at annual time scales (Tucker and Hancock, 2010). Long term data sets are required for this type of analysis as well as an assessment of alternative calibration methods (Burt and McDonnell, 2015; Seibert and McDonnell, 2015). The aim of this paper is to employ and build on (near decadal time scale) sediment data described in Hancock et al. (2017) for two undisturbed forested catchments. Specific objectives are to:

- a. Model sediment transport in undisturbed forested catchments using a LEM
- b. Develop and evaluate a calibration process
- c. Demonstrate the model's ability as a tool for erosion prediction and
- d. Assess the sensitivity and applicability of the model for sediment increase due to fire or other forest disturbances.

2 Site description

Established in 1974 (Cornish, 1993), the Karuah Hydrology Research Area (KHRA) lies approximately 85 kilometres north of Newcastle, New South Wales, Australia in Chichester State Forest (Figure 1) and has recently been described in Hancock et al. (2017). The site comprises a series of eight 13 – 97 ha catchments located in the headwaters of the Telegherry River, a tributary of the Karuah River (Cornish 1993; Webb et al. 2012b). Here we focus on two catchments (Crabapple and Sassafras) which have not been disturbed by forest harvesting. However, the Crabapple catchment contains access roads and stream crossings constructed in 1982 (Figure 2).

The study area consists of a Carboniferous sequence of weathered sedimentary rocks composed of mudstones, siliceous siltstones and limestone lenses formed in a depositional marine environment (Peou 1977). Soils can be organised into euechrozems, brown and yellow

podzols and xanthozems. They are highly structured and friable, with most containing significant organic matter and in general, are regarded as deep (Elliott, 1977).

The site has a moist, warm temperate climate (Cornish 1993) with mean annual rainfall ranging between 1450 and 1750 mm, depending on elevation (Table 1). There is typically a seasonal maximum during summer months and a seasonal minimum in the winter months. Maximum temperature varies with elevation. Summer temperatures average 28°C (at 450 m) and 24°C (at 940 m), and in winter minimum temperatures throughout the area drop to an average of 3°C.

Prior to 1983, the catchments were predominantly undisturbed forest lands dominated by mature eucalypts ranging from 100 to over 500 years in age (Cornish 1993) (Figures 3 and 4). The area is dominated by tall, wet sclerophyll forest (> 35 m), predominantly eucalypt; Sydney Blue Gum (*Eucalyptus saligna*; 43% of catchments), Silvertop Stringybark (*E. laevopinea*; 23%), some New England Blackbutt (*E. andrewsii*), and rainforest (32%) (Figures 2 and 3). Canopy cover is quite high, varying from 90% to 55% with an average coverage of 72% (Cornish and Vertessy, 2001; Law and Chidel, 2002). As mentioned, the study sites examined here, Crabapple and Sassafras, retain mature forest. In 2011 the Crabapple catchment had a measured stocking rate of 975 stems ha⁻¹ and a basal area of 101.4 m² ha⁻¹ (Webb et al., 2012b).

2.1 Catchment geomorphology

In terms of catchment shape, area and elevation the two catchments, Crabapple and Sassafras, are quite different (Figures 1 and 2, Table 2). The two catchments have different shapes and sizes (Sassafras is nearly twice as big as Crabapple) as well as different relief. However, when area and elevation are non-dimensionalised (hypsometric curve and integral),

they are quite similar (Figure 5, Table 2). The hypsometric curve (Langbein, 1947) is a non-dimensional area-elevation curve. The non-dimensionalisation of the curve allows ready comparison of catchments with different area and steepness (the area below the hypsometric curve is the hypsometric integral).

The hypsometric curve can be used as an indicator of the geomorphic maturity of catchments (Hancock, 2005). Willgoose and Hancock (1998) demonstrated its linkage with erosion processes, catchment geometry and network form. A further advantage of this approach is that it is not greatly affected by random aspects of the channel network while still being sensitive to changes in the parameters of the erosion physics. Strahler (1952, 1964) classified landforms into youth, mature and monadnock characteristic curves indicating increasing catchment age - with the Crabapple and Sassafras catchments being at the mature stage. Willgoose and Hancock (1998) demonstrated that these characteristic shapes (i.e. youth, mature, monadnock) were also consistent with different catchment erosion processes.

The catchment area-slope relationship can also provide valuable information on catchment geomorphology and erosion processes (Montgomery and Dietrich, 1988; Montgomery and Dietrich, 1989; Tarboton et al., 1992; Montgomery and Foufoula-Georgiou, 1993; Moglen and Bras, 1994; Willgoose, 1994; Rodriguez-Iturbe and Rinaldo, 1997; Hancock, 2005). The area-slope relationship of a catchment is the relationship between upslope area draining through a point versus the slope at that point where

$$S = K A^{-\alpha} \quad (1)$$

where S is slope at a point (m/m), A is area draining through the point (m^2), α and K are an exponent and constant respectively which need to be fitted. If the site is at or close to equilibrium (i.e. a mature catchment as indicated by hypsometry) then the catchment will comply with the log-log area-slope relationship (Willgoose, 1994).

Two characteristic regions are typically observed (Figure 6). Region A (small catchment areas) is dominated by inter-rill erosion, rainsplash and soil creep. That is, erosive processes that tend to round or smooth the landscape. As catchment area increases, a break in gradient occurs. Region B is where slope decreases as catchment area increases. This region of the catchment is dominated by fluvial erosive processes, that is, those processes that tend to incise the landscape. The area-slope relationship has been demonstrated to be sensitive to processes characterising diffusive and fluvial processes (Hancock et al., 2002).

Geomorphically, despite their different sizes and relief, the catchments have similar hypsometry and area-slope relationships. This suggests that they have similar geology, soils, and therefore similar hydrology and sediment transport (McDonnell, 2013).

3 Field data

To calibrate and evaluate LEM predictions sediment transport data is required. Below we briefly describe the site hydrological data, bedload and suspended sediment measurement. Topographic data for determination of catchment characteristics as well as for employment in the LEM is also described. Further detail can be found in Hancock et al. (2017).

3.1 Hydrological data measurement

A sharp-crested V-notch weir, installed on, and concreted to bedrock at the outlet of each catchment allowed stage recording within stilling wells from 1975 (Figure 3). Measurements from 1975–1989 were made using chart recorders and are now digitised. Later measurements were from optical shaft encoders with data recorded on dataloggers at 6-min

intervals. Discharge rating curves have been established and updated over the years (Cornish, 1993; Webb et al., 2012b).

3.2 Catchment total sediment load

To determine suspended sediment both catchments were instrumented with an automatic pump water sampling system (ISCO 3700), a data logger, optical shaft encoder and a staff gauge (power by 12 V batteries, charged by a solar panel). Water samples were automatically extracted by a stage-activated sampler (ISCO 3700) during flood events on the rising and falling limbs of the hydrograph. Additional samples were collected fortnightly during periods of baseflow. Data was routinely downloaded fortnightly and water samples were retrieved from the automatic samplers. These were analysed in the laboratory for turbidity and suspended sediment concentrations, following standard methods (APHA 1998). Water sample data was collected for approximately 8 and 8.5 years for Crabapple and Sassafra catchments respectively between 2004 and 2012 (Hancock et al., 2017).

To quantify bedload, the settled material behind each weir was manually removed by shovel and bucket. Each bucket (12 litres in volume) was carefully filled and the number of buckets counted as removal progressed. The material removed from each weir was relocated downslope of the respective weir. Volume of material was converted to units of mass using a bulk density of the stream sediment.

Annual total sediment load was calculated by the addition of suspended sediment and bedload. Further detail on the suspended sediment and bedload measurement method is described in Hancock et al. (2017).

3.3 Topographic data

Topographic data in the form of a digital elevation model (DEM) is required for use in a LEM and for the determination of geomorphic descriptors in Section 2.1. The DEM has to accurately and reliably represent the catchment of interest by having a grid small enough to capture hillslope and catchment morphology. Hancock (2005) found that a 5-10m grid size DEM was usually sufficient to represent hillslope and catchment topography.

Here the topographic data consisted of a 1 metre resolution Light Detection and Ranging (LiDAR) data set supplied by RPS Australia East Pty Ltd. The data was collected in 2011. Average point data was 2 points per m². Vertical and horizontal accuracy was +/-0.2m and +/-0.4m respectively. From this high resolution DEM data, catchment area, slope, upslope contributing area, hypsometric curve and integral were derived.

4 Soil erosion and Landscape Evolution Models

In the 1970s and 1980s a number of physically based computer models that predict landscape evolution were developed (Hancock and Tucker, 2010). The goal of these first models was to examine landscape evolution in terms of long term erosion over geological time scales. These models all use a mesh of grid cells to represent a catchment (Ahnert, 1976). Over time and with increasing computer processing power these models have evolved to include more complex surface and subsurface processes as well as larger model domains (Willgoose et al., 1991a, b; Braun and Sambridge, 1997; Coulthard, 2001; Tucker *et al.*, 2001; Coulthard et al., 2013). These numerical models allowed insights into fluvial and diffusive erosion processes as well as how geological processes (such as uplift and mass movement) together with climate influence catchment evolution. It was also realised that while these models could be used to examine landscape processes at geological time scales,

they could also be used to examine short-term (i.e. annual time scale) landscape behaviour. However, many of these models have only undergone the most cursory evaluation for their accuracy and reliability for applied projects. All models have their strengths and weaknesses and a summary of key attributes is described in Tucker and Hancock (2010). This is the first time such a model has been assessed for relatively steep, high rainfall and densely forested catchments. Here we focus on the SIBERIA model. SIBERIA has been tested and evaluated mostly for proposed post-mining landforms (Evans and Willgoose 2000; Evans et al., 1999, 2000; Hancock et al., 2000, 2002; 2007; Willgoose and Riley 1998) as well as limited testing for natural catchments (Hancock et al., 2008; Hancock, 2009; Martinez et al., 2009). The model, being one of the first to be developed is one of the more ‘simple’ LEMs currently available, and therefore should be amenable to calibration and validation in the environment here. The rationale here is that if a more basic LEM cannot operate in this environment, then other more complex models may have difficulty.

SIBERIA mathematically simulates the geomorphic evolution of landforms subjected to fluvial and diffusive erosion (Willgoose et al., 1991a-b). The model employs hydrology and erosion models at annual and longer time scales. The sediment transport equation of SIBERIA is:

$$q_s = q_{sf} + q_{sd} \quad (2)$$

where q_s ($m^3/s/m$ width) is the sediment transport rate per unit width, q_{sf} is the fluvial sediment transport term and q_{sd} is the diffusive transport term (both $m^3/s/m$ width). The model is usually calibrated to operate at annual time scales.

The fluvial sediment transport (erosion processes resulting from flow concentration) expression (q_{sf}) is based on the Einstein-Brown equation and models incision of the land surface and can be expressed as:

$$q_{sf} = \beta_1 Q^{m_1} S^{n_1} \quad (3)$$

where Q is the discharge per unit width ($m^3/s/m$ width), S (metre/metre) the slope in the steepest downslope direction and β_1 , m_1 and n_1 are calibrated parameters.

Diffusive erosion (or creep term), q_{sd} , is:

$$q_{sd} = DS \quad (4)$$

where D ($m^3/s/m$ width) is diffusivity and S is slope. The diffusive term models smoothing of the land surface and combines the effects of creep and rain splash.

SIBERIA does not directly model runoff but relates discharge to area (A) draining through a point as;

$$Q = \beta_3 A^{m_3} \quad (5)$$

where β_3 is the runoff rate constant and m_3 is the exponent of area ($m^3/s/m$ width). The above parameters incorporate soil and surface properties such as erodibility, infiltration, macropores and surface roughness.

The advantage of SIBERIA over more traditional erosion models (i.e. RUSLE, Wischmeier and Smith, 1978) lies in its use of digital terrain maps for the determination of drainage areas and representation of catchment topography as well as its ability to efficiently adjust the landform elevations with time in response to the erosion and deposition that occurs. This is, if more sediment enters a point than exits, elevation will increase. Conversely, if more sediment exits a point than enters, the elevation decreases. At every time step SIBERIA adjusts catchment elevations based on this process. The model can operate at DEM grid scales from less than a metre up to many tens of metres depending on the scale of the process of interest. For example small gullies and rills can be examined at less than 0.5m (Hancock et al., 2000) up to long-term studies over entire landscapes (Willgoose and Riley, 1998).

A more detailed description of SIBERIA can be found in Willgoose et al. (1991a-c).

5 SIBERIA input parameters

A focus of this project is the calibration of the SIBERIA model. This requires calibration of the fluvial sediment transport equation (Equation 2) and area-discharge relationship (Equation 4). Two methods can be used and are described below in order of complexity. Firstly, parameters can be inferred from the catchment DEM. Secondly, parameters can be derived from stream hydrology and sediment transport data.

5.1 Inferring parameters from DEMs and catchment properties

Willgoose (1994) demonstrated that the slope of the fluvial section of the area-slope relationship (α) (Equation 1, Section 2.1) is:

$$\alpha = (m_3 m_1 - 1)/n_1 \quad (6)$$

where m_3 is the exponent of discharge draining through a point in Equation 4 and m_1 and n_1 are exponents in the SIBERIA sediment transport (Equation 2).

Here the area-slope relationship was extracted from the DEM for both the Crabapple and Sassafras catchments and equation 6 fitted to the log-log linear component of the area – slope curve (Figure 6). Using this approach a value for α of 0.14 and 0.17 was determined for the Crabapple and Sassafras catchments respectively.

The values of m_1 and n_1 vary widely but for most fluvial systems they both range between 1 and 3 (Kirkby, 1971). Using an assumed value of $n_1 = 2$ for wide channel flow as suggested by Henderson (1966) and described in Willgoose et al. (1991a-b), and a value for m_3 of 1, the value for m_1 is 1.28 and 1.34 for the Crabapple and Sassafras catchments, respectively. These values of m_1 and n_1 are within the range of values for fluvial process

dominated catchments suggested by Kirkby (1971) assuming a spatially uniform sediment production rate. Therefore the parameters are what could be reasonably expected for the catchments examined here.

While the DEM can provide information on the constants m_1 and n_1 , the erodibility parameter β_1 still requires determination. Here we use the textural properties of the soil to determine β_1 . It has long been recognized that soil properties influence erosion rates. While there are many factors, such as organic matter content, electrical conductivity, and rock content that contribute to soil erodibility, one of the strongest influences on erodibility is the soil particle size distribution (Sheridan et al., 2000). Consequently, the textural properties or particle size distribution as well as the physical attributes of soil can be used to provide an indication of erodibility and derive SIBERIA parameters.

For this study soil particle size data were obtained from soil cores collected from representative hillslopes in the study catchments. Further samples could be collected to better capture soil variability across each catchment (i.e. on a 100m by 100m grid) but the samples analysed here were considered sufficient for the purposes of this initial investigation.

Soil samples were air-dried in an oven at 40°C for approximately 7 days. Samples, once dried, were gently disaggregated and mixed with a mortar and pestle. Samples were then passed through a 2 mm sieve, with the coarse fraction (> 2 mm) set aside. The remaining fines fraction (< 2mm) was used for analysis of particle size by sieve analysis (for the >2mm soil fraction) and hydrometer (for the <2mm soil fraction) from soil samples collected on the study site. This analysis resulted in an average of 17.5% sand, 33.8 % silt and 48.7% clay, with the soil classified as a silty clay (Hazelton and Murphy, 2007).

Soil textural properties can be used to calculate a K value based on the RUSLE methodology or database (see K values listed for different soils listed in Hazelton and Murphy, 2007) (Evans and Loch, 1996). The RUSLE K value can be considered to be

equivalent to the SIBERIA β_1 (Equation 2) (Willgoose, 2012). Using this classification based on soil texture, Hazleton and Murphy (2007) suggest a K value of 0.025.

For many sites where there is bare earth or where the site has been degraded with little or no vegetation (i.e. mine sites with a bare non-vegetated surface or a surface with vegetation removed by fire – discussed later), this erodibility (K) value can be used directly in the model. However, many sites have a rock cover or armour. In the case here, a dense forest vegetation cover exists. Similar to the RUSLE K factor, the RUSLE C (Wischmeier and Smith, 1978) factor can be used to determine the expected erosion reduction due to vegetation, an important consideration given the catchments examined here and the forested vegetation cover.

There is quite a lot of data on the role of vegetation and a C factor can be directly determined from tables (Wischmeier and Smith, 1978) from a variety of sources (Blanco and Lal, 2008) (Figure 3, bottom). Overseas data suggest that a C value of 0.001 may be appropriate for a forest with at least 90% canopy cover with a 100% litter cover such as that here (Blanco and Lal, 2008). However here we use a C value determined from a similar forest environment in the south-east of Australia. Jamshidi et al. (2012) examined a range of forest types and catchments and suggest a range of C values from 0.001 to 0.01. Here we use a median value of 0.005. The SIBERIA β_1 value is then determined by multiplying the K value by the C value (Table 3).

In this paper these parameter sets for the Crabapple and Sassafras catchments are named as ‘Inferred’ as they are not directly derived from any discharge or sediment transport data.

5.2 SIBERIA parameters derived from field hydrology and sediment transport data

The most reliable parameters are derived from field data where there are known catchment areas and slopes, and all water and sediment discharge data are collected for a series of significant runoff events. To calibrate the erosion and hydrology models, complete data sets of sediment loss, rainfall and runoff for discrete runoff events are therefore collected. The data can then be used in a multiple regression of discharge and sediment output to optimise the hydrology and sediment transport equation parameters.

This method is the most reliable as it is site based and therefore is representative of the site materials and sediment transport processes over the entire catchment. Any data obtained is an integrated value from the study catchment. However this field based approach requires many rainfall events and therefore time (i.e. the more runoff events the more robust the calibration). This makes such field plots costly to setup and to maintain. Details surrounding the field plot parameterization process are described in detail by Evans et al. (1999, 2000) and Hancock et al. (2000).

The hydrology and erosion model parameters in SIBERIA represent temporal average properties of the runoff and erosion processes occurring on the landscapes. Any parameter values derived from a runoff event (i.e. rainfall-runoff plots) represent instantaneous values and must be integrated over time to yield temporal average values. Therefore instantaneous measurements of discharge and grab samples of runoff containing sediment while useful, may not provide reliable parameters that are representative of long-term erosion rates

Here sediment output data from the Crabapple (Figure 7) and Sassafras (Figure 8) catchments were determined from discharge and total sediment load (Hancock et al., 2017). Suspended sediment was collected between 2004 and 2012 (Table 2). Average annual suspended sediment yields were 14.23 and 13.60 tonnes per year for the Crabapple and Sassafras catchments, respectively. Bedload output from Crabapple and Sassafras was 1.5 t/yr and 2.02 t/yr (Table 2) respectively. Total load for Crabapple and Sassafras catchments was

calculated by the addition of both bedload and suspended load which was 15.63 and 15.68 t yr⁻¹ respectively (Table 2) (Hancock et al., 2017).

To calibrate the hydrology and sediment transport (Equation 3), all storms were identified in the discharge record and whole complete storm and sediment transport data was aggregated for each catchment (Figure 7 top and 8 top). This aggregated storm data was used in a multiple regression with parameters β_1 , m_1 , n_1 , β_3 and m_3 determined when the strongest statistical relationship was obtained (Crabapple $r=0.94$, $p<0.01$; Sassafras $r=0.98$, $p<0.01$). This process demonstrated that over the eight year period the majority of storms produced little or no sediment (Figure 7 top and 8 top) and the majority of sediment was produced by a small number of storms. Interestingly, this process produced parameters similar to that described in Section 5.1 using the inferred approach (Table 3). Here these parameters for the Crabapple and Sassafras catchments are termed as ‘Field’ parameters as they are determined from the field measurement of discharge and sediment.

6 Model setup

The SIBERIA model was run using the LiDAR derived DEM for each catchment as displayed in Figure 2 and described in Section 3.5. Before use each DEM was pit-filled to remove any artificial low points. Each catchment had an outlet 3 nodes wide (3m) which represented the approximate width of the weir where the discharge and sediment were measured. All sediment was routed through this point. SIBERIA was then run using both the Inferred and Field parameters for both catchments for a period of ten years representing the approximate length of the field data collection.

7 Results and discussion

While extensively employed in both theoretical (Ahnert, 1976) and applied environments, there has not been a lot of research into the calibration and validation of LEMs (Tucker and Hancock, 2010). If a LEM is to be reliably used then it needs to be assessed for its accuracy and reliability over both the short (annual) and long-term (millennia) time periods. However, the reason why LEMs have not been extensively tested is that there is a dearth of long-term field data which can be used. If the models are not reliable in the short-term, how can we expect any long-term prediction to be correct (Willgoose, 2005)?

The Karuah data set provides an almost decadal scale record of total sediment load with which to assess sediment transport (Hancock et al., 2017; Webb et al., 2012b). There are few sites in Australia, let alone globally, which have such long-term data for the type of assessment conducted here (Burt and McDonnell, 2015). Further, the two catchments examined here are largely undisturbed (although Crabapple has 2 minor access roads) which allows the model to be tested without the complexity of land use disturbance.

However, an issue not addressed here, is that of extreme events and longer term climate trends. How can we be certain that the eight years of field data truly represents the landscape processes that ultimately shape the catchment? The runoff and sediment transport data was collected over a period which was relatively wet. What happens in times of drier climate where there may be less vegetation and infrequent but high intensity storms? In earth science time scales, this is an impossibly short calibration time period employed here. Can these parameters, even though they have been shown to be reliable over the time period examined, be used to assess landscape evolution at the century to millennial time scales? This is an area which we do not address here and focus on the relatively short-term and calibration of the model for the here and now. The work here demonstrates that longer term field data from this site and others is needed to better develop and assess climate and parameterisation extremes.

7.1 Catchment sediment output

Evaluation of the SIBERIA model sediment output has mostly been performed with small plot studies (Evans and Willgoose, 2000; Evans et al., 1999; 2000; Hancock et al., 2000; 2016) and environmental tracers such as ^{137}Cs (Hancock et al., 2008; Martinez et al., 2009). Here the SIBERIA predicted sediment output (Table 3) demonstrated a good match with the Crabapple catchment simulation (producing 15.0 and 16.9 t/y for the Inferred and Field parameters respectively) and Sassafras simulations (producing 13.3 and 17.7 t/yr respectively) (Table 3). The results demonstrate that there is little difference between the predicted sediment output using either the Inferred or Field derived parameters for this site. Therefore the model provides reliable results in this setting.

The scaling of catchment sediment output for catchments of different sizes has long been debated (Walling, 1983; Parsons et al., 2006). Here, in terms of spatial and temporal scaling, the field sediment transport data demonstrate that over the eight year period the two catchments produced similar sediment outputs despite differences in catchment size, shape and relief. Crabapple is smaller than Sassafras, it has a higher average slope and therefore less sediment storage capacity. Therefore the differences in catchment size and shape provide a good test of both the calibration process and demonstrate that SIBERIA is scaling sediment output correctly.

7.2 Model calibration

The calibration of SIBERIA has in the past been based on relatively short term plot studies using small catchment areas (Evans and Willgoose, 2000; Evans et al., 1999; 2000;

Hancock et al., 2000; 2016); an interesting finding here is that both the Inferred and Field derived model parameters were similar for the individual catchments. The similar hypsometric curves and integrals together with similar area-slope properties demonstrate catchments with similar maturity and elevation properties thus suggesting that they have similar hydrology and sediment transport characteristics (Langbein, 1947; Strahler, 1952; 1964; Willgoose and Hancock, 1998; Willgoose, 1995).

The results show that at this site, reliable calibration data can be obtained using parameters derived from the DEM (area-slope relationship) as well as erodibility based on the RUSLE methodology where there is limited field data (Sheridan et al., 2000; Jamshidi et al., 2013; Blanco and Lal, 2008). The results also suggest that long-term field data may not be needed for calibration. However, the findings here are for one site only and more field data from other sites is needed to fully evaluate this methodology.

While eight years of data collection period is not long in a geomorphic sense, it provides a good basis with which to evaluate a soil erosion and landscape evolution model (Tucker and Hancock, 2010). There are few data sets globally which provide such long-term data for relatively undisturbed environments where reliable data is available. The field data demonstrates that there are many runoff events that produce minimal sediment discharge while low return frequency events are needed to provide reliable field data with which to calibrate a LEM (Evans and Willgoose, 2000; Evans et al., 1999; 2000). An examination of sediment discharge and total sediment load for the major events (Figures 7 and 8 top) demonstrates that if any of these major events were missing or a further event was available a different set of parameters may result. This again highlights the need for reliable long-term field data (McDonnell, 2013; Burt and McDonnell, 2015). Willgoose et al (1991a-c) suggested that in terms of sediment output it is the 1:2.33 year event that is the most

geomorphically effective. The results here clearly demonstrate that a limited number of events produce the most output and this fits with the concept of Willgoose et al. (1991a-c).

7.3 Sediment source and field verification

While we have demonstrated that SIBERIA can predict sediment output that approximates that of the field data, a further question is, where is the sediment coming from in the catchments? Or an alternative question is, is the model producing the right answers for the wrong reason? Without long-term hillslope measurement and observation this is a difficult question to address.

Inspection of the creek bed and banks upstream of the weirs demonstrates that the bed and banks are largely stable with little erosion or bank instability (Figure 4). The hillslope also has a dense tree canopy as well as a dense leaf litter cover on the forest floor (Figure 3, bottom). This suggests that rainfall will be delivered to the ground surface as either leaf drip and or stem flow. Field inspection of both catchments found no evidence of hillslope rill or gully erosion. Therefore the measured material at the weirs is likely sourced from the hillslope via non-incisive erosion processes. An unpublished study using the environmental tracer ^{137}Cs found high concentrations both in hillslope soil as well as in fine depositional material samples from behind each of the weirs (Hugo, 2016). This suggests that surface material is being transported from the hillslope to the creek and that the sediment in the creek is hillslope material. Given the dense vegetation and litter cover, the exact process of this sediment transport is speculative. To better understand this process, erosion pins (using the same methods as Hancock and Lowry, 2015) have been installed along a hillslope transect in the Sassafras catchment. We also plan to undertake high resolution surveying of the Sassafras transect each year or after major rainfall events.

Evaluating cross-sections from the catchments after 10 years of modelled erosion demonstrates that no significant erosion has occurred and what has occurred is in the form of

sheetwash (Figure 9). That is, the model does not produce any incision or gully and matches field observation. This observation provides confidence in that the parameter set used here ($m_1 \sim 1.3$, $n_1 \sim 2$), which Kirkby (1971) suggests represents non-incisive erosion processes with little gully, is reliable just based on field observation of the site. This finding suggests that any parameter derivation, particularly that determined by inferred means should be verified by observation.

7.4 Other applications and sensitivity analysis

While the focus here is on calibration and validation of the SIBERIA model for an environment that could be classed as undisturbed, the model and its parameterisation process also has other functionality such as quantifying the effects of forest regrowth on sediment loss as well as the effects of fire. Below we explore this capability which also acts as a sensitivity analysis of the model and its parameters, firstly, by examining the potential impact of forest regrowth after harvesting and secondly, after a forest fire (Prosser and Williams, 1998; Dragovich and Morris, 2002; Lane et al., 2006; Bladon et al., 2014).

Recent work has found that post-harvest sites in the KHRA provide less sediment than that of the undisturbed sites described here (Hancock et al., 2017). This reduced sediment load was suggested to be the result of more dense regrowth in the post-harvest areas, as described by Cornish (2001). To evaluate this process, the C factor was reduced to 0.003 (as suggested by Jamshidi et al. (2013)) and a new β_1 calculated (named Inferred (regrowth)) (Table 3). The simulations were rerun with this new (reduced) β_1 which produced lower sediment output matching the scale of the reduction found post-harvest (Table 3) (Hancock et al., 2017). This demonstrates the usefulness of the model for the assessment of

different landscape management options. Therefore the model is sensitive to parameterisation.

The effects of fire on forest ecosystems is well recognised. The SIBERIA model can easily be employed to assess the effects of fire on sediment loads. Given that the erosion reduction by vegetation is directly incorporated in the parameter β_1 , this parameter can be adjusted (increased) by assuming the ground cover is bare earth (a Cover Factor of 1). This results in a large increase in β_1 (named Inferred (fire) (Table 3)). Running the SIBERIA model with this increased β_1 produces an order of magnitude increase in sediment output compared to the measured field data (Table 3). This degree of increase in erosion is to be expected post-fire (Prosser and Williams, 1998; Dragovich and Morris, 2002; Lane et al., 2006; Bladon et al., 2014) and highlights the usefulness of the model.

While not examined here, the model can also be used for long-term (centennial to millennial scale) landscape evolution assessment under current undisturbed vegetation conditions or with different catchment and forest harvesting scenarios (Hancock et al., 2002; 2008b). SIBERIA also lends itself well to catchments with spatially variable hydrology and sediment transport parameters. The model parameters (using the methodology described here) could also be extrapolated to examine significant changes in climate and resultant changes in both vegetation and rainfall. Therefore the model would be a useful tool to assess any high risk and or controversial forest harvesting sites (an issue not examined here).

7.5 Model limitations

LEMs, like all models, are simplifications of reality and only employ a simple set of equations and parameters that can never encompass the entire set of spatial and temporal processes and patterns. While the model has been shown to be reliable here and we speculate

that it is likely to work in other steep forested catchments, it needs testing for different environments and climates. A weakness here is, while the 8 years of field data is very good in global terms and is relatively long-term, much longer term data sets are needed to better calibrate and evaluate LEMs. Also, to fully assess the immediate disturbance caused by forest harvesting and fire, hydrology and sediment transport data and parameters are needed from immediately after any disturbance.

We have only examined one LEM here (SIBERIA). Other suitable LEMs such as CAESAR-Lisflood (Hancock, 2009; Coulthard et al., 2013) can be used with much less calibration effort and this LEM is currently being tested for the sites here. CAESAR-Lisflood operates at hourly time steps and therefore provides a much higher temporal assessment capability. However, the real strength of any model is the ability to test hypotheses and examine different climate and landscape management scenarios. Even without a rigorous calibration and validation process (as described here) LEMS can provide insights into both short and long-term landscape behaviour.

8 Conclusion

Soil erosion and LEMs have been employed across a range of both natural and disturbed landscape systems and are useful tools which can aid landscape management. They purport to be useful for a wide range of environments and it is essential that we fully assess their reliability. Here two methods were used to calibrate SIBERIA. The first used information determined from the topography of the catchment and soil properties. The second method used stream hydrology and sediment data. The findings demonstrate that while the method using stream hydrology and sediment data is the most rigorous as it uses site specific data, the method using topographic data derived from DEMs provides similar results in this

environment. This provides confidence in the application of the model in environments where there is a lack of site specific discharge and sediment data.

Also of significance here is that this is the first time that SIBERIA has been employed in a steep slope forested environment. The model proved reliable and may provide an alternative to other soil erosion models (i.e. RUSLE and WEPP). This demonstrated reliability of the model also provides confidence in its application to other forested environments and in assessing the potential effects of disturbances such as wildfires or forest harvesting.

There is a paucity of sites globally where there is long-term catchment sediment transport data suitable for evaluation of LEMs. We highlight the need for further sites and continued evaluation of LEMs for their reliable employment.

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Table 1. Rainfall (mm) across the Karuah study area. The data is an average of the raingauges K1, K4 and K4 displayed in Figure 1.

year	Annual rainfall
2005	1566
2006	1439
2007	1549
2008	1825
2009	1912
2010	1580
2011	1865
2012	1113

Table 2. Catchment characteristics, geomorphology and sediment loads for the Crabapple and Sassafras catchments.

catchment	Area (ha)	Mean elev. (m)	Relief (m)	Hyp. Integ.	Mean slope (deg.)	Bed load (t/yr)	Sus. sed. (t/yr)	Total load (t yr ⁻¹)
Crabapple	14.7	804	266	0.42	24.3	1.4	14.2	15.6
Sassafras	25.3	645	407	0.43	22.5	2.0	13.7	15.7

Table 3. SIBERIA parameters from both the field data and fitted to the stream hydrology and sediment data.

parameters	β_1	m_1	n_1	β_3	m_3	SIBERIA output (t/yr)
Crabapple						
Inferred	0.000125	1.28	2	1	1	15.0
Field	0.00016	1.31	2	1	1	16.9
Inferred (regrowth)	0.000075	1.28	2	1	1	9.0
Inferred (fire)	0.025	1.28	2	1	1	290.9
Sassafras						
Inferred	0.000125	1.23	2	1	1	13.3
Field	0.00014	1.26	2	1	1	17.7
Inferred (regrowth)	0.000075	1.23	2	1	1	8.1
Inferred (fire)	0.025	1.23	2	1	1	372.3

A computer based Landscape Evolution Model is calibrated for a forested environment

The model (SIBERIA) reliably predicts field measured sediment transport rates

Also, pattern of erosion and deposition is matched with field observation

The model offers huge potential for quantifying sediment transport in such environments

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