18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Comparison of landscape approaches to define spatial patterns of hillslope-scale sediment delivery ratio

Vigiak, O.[1], **L.T.H. Newham**[2], **J. Whitford**[1], **A. Melland**[3] **and L. Borselli**[4]

[1] *Department of Primary Industries, Future Farming Systems Research division, Rutherglen centre, Rutherglen, Victoria. Email: olga.vigiak@dpi.vic.gov.au*
[2] *Integrated Catchment Assessment and Management (iCAM) Centre, The Fenner School of Environment and Society, The Australian National University, Australian Capital Territory*
[3]*Teagasc, Environment Research Centre, Johnstown Castle, Wexford, Co. Wexford, Ireland*
[4] *CNR-IRPI, Research Institute for Geo-Hydrological Protection, Via Madonna del Piano, 50019 Sesto Fiorentino (FI), Italy*

Abstract: A sediment delivery ratio (SDR) is that fraction of gross erosion that is transported from a given catchment in a given time interval. In essence, a SDR is a scaling factor that relates sediment availability and deposition at different spatial scales. In this paper, we focus on hillslope-scale SDR, i.e. the ratio of sediment produced from hillslopes to that delivered to the stream network. Factors that affect hillslope water movement, and thus entrainment or deposition of sediments, ultimately affecting the SDR, include upslope area, climate, topography, and soil cover. In erosion models, SDR is usually treated as a constant parameter. However, the use of spatially variable SDRs could improve the spatial prediction of the critical sources of sediment, i.e. identification of those areas directly affecting stream water quality. Such information would improve prioritisation of natural resource management effort and investment. Recent literature has described several landscape approaches to represent SDR variability in space, some of which account only for topography, whilst others consider topography and soil cover characteristics. The aim of this study was to evaluate four landscape approaches for their ability to depict spatial patterns of SDR in the Avon-Richardson catchment in the semi-arid Wimmera region (Victoria, South-east Australia). Erosion was assessed using a semi-distributed model (CatchMODS) with disaggregation based in subcatchments of around 40 km^2 area. Hillslope gross erosion was assessed with a RUSLE approach. By applying the four landscape approaches using DEM and estimates of land use cover, four landscape index subcatchment distributions were calculated. These were normalised into standard distributions. Then, a sigmoid function was used to transform the standardised indices into SDR-index distributions ranging from zero to one. Finally, subcatchment SDRs were estimated as the product of the SDR-index by a whole-of-catchment SDR value that was estimated by calibration against sediment loads measured at five gauging stations of the study area. The major sources of hillslope erosion were modelled to be located in the southern hilly areas of the catchment. However, a topographic convergence approach predicted as well important contribution of hillslope-erosion sediment loads coming from the eastern flatter cropping land. The introduction of landscape-variable SDRs improved the overall goodness-of-fit of modelled versus observed sediment loads at five gauging stations located in the catchment for only the topographic convergence approach. However, the limited number of observations (11), the location of some gauging stations downstream of active gully erosion, and the lack of gauging stations monitoring the north-eastern part of the catchment hindered the assessment of which spatial distribution of hillslope erosion best represented the real catchment conditions. Further research is needed to define the relationship between landscape indices and SDR; and to evaluate the spatial distribution of erosion against more complete field evidence.

Keywords: *Sediment delivery ratio, CatchMODS, landscape index, spatial prioritisation, soil erosion, connectivity*

1. INTRODUCTION

A sediment delivery ratio (SDR) is that fraction of gross erosion that is transported from a given catchment in a given time interval. In essence, a SDR is a scaling factor that relates sediment availability and deposition at different spatial scales (Lu et al., 2006); in the modelling practice, it also allows accounting for the limitations of using erosion assessment models created for the field scale to larger spatial units. In erosion models, SDR is usually treated as a constant parameter through time and space. However, a spatially variable SDR could improve an erosion model's capability in locating the sources of sediment affecting stream water quality, and in prioritising natural resource management investments. At the hillslope scale, the SDR accounts for deposition of particles along the hillslope. Factors that affect hillslope water movement include upslope area, climate, topography, soil properties, and soil cover. These factors should therefore exercise control over SDR spatial distribution. Recent literature proposed several landscape approaches to represent SDR variability in space, some of which account only for topography (e.g. Rustomjii and Prosser, 2001), whilst others consider both topography and soil cover characteristics (Ferro and Minacapilli, 1995; Mitasova et al., 1996; Borselli et al., 2008). Lu et al. (2006) developed a theoretical approach to regionalise the SDR of the Murray Darling basin based on topography, surface roughness, particle size, and rainfall properties.

The accuracy of spatial patterns depicted by the landscape approaches has seldom been evaluated. The aim of this study was to compare the spatial distribution of SDR as predicted by four landscape approaches in the Avon-Richardson catchment in the semi-arid Wimmera region in Victoria, south-east Australia.

2. STUDY AREA

The Avon-Richardson catchment is an endorheic basin that extends over 3300 km^2 of the Wimmera region of south-east Australia (Figure 1). Soils are mainly deep and clayey, with uniform or duplex soil profile (Melland et al., 2008). Three agro-climatic zones are distinguished: grazed uplands in the south (average rainfall approximately 500 mm a^{-1}), mixed farming (i.e. combination of grazing and cropping) in the mid-catchment (average rainfall approximately 450 mm a^{-1}), and flat croplands in the north (average rainfall approximately 400 mm a^{-1}). Grazing management consist mainly of set stocking on annual pastures. In the mixed farming areas, cropping land expanded from 20% in the 70s to around 40% in the last decade. In the flat croplands, almost all land is cultivated with broad-acre crops. Cultivation intensified over time: in the 70s cultivation systems consisted of wheat-fallow rotation in the mixed farming and wheat-barley-pasture-fallow rotations in the flat croplands. Starting from the 80s, rotations changed to wheat-barley-fallow in the mixed farming, and to canola-wheat-barley-legume in the flat croplands (Vigiak et al., 2008).

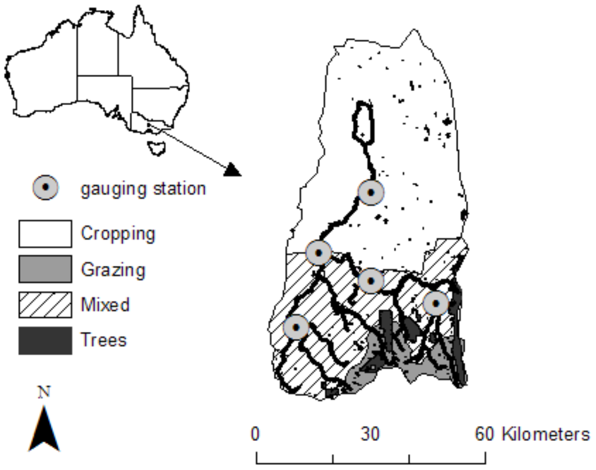

Figure 1. The Avon-Richardson catchment in Victoria. From north to south, the main farming systems are cropping, mixed farming and grazing. Suspended sediments are monitored at five stream gauging stations.

Suspended sediments are monitored twice a month at five gauging stations of the Avon and the Richardson Rivers (Figure 1). Data analysis showed that only 168 data entries at discharge larger than zero were available. Given the paucity of data, annual suspended sediment loads were estimated with a ratio-based load estimation method (Letcher et al., 1999). Suspended sediment yields averaged at 2 t km^{-2} y^{-1} across the catchment.

3. CATCHMENT-SCALE EROSION MODELLING FRAMEWORK

Two main sources of sediments are active in the Avon-Richardson catchment, i.e. sheet and rill erosion from hillslopes and gully erosion along drainage depressions in the south of the catchment. Both sources of sediments were accounted for using the catchment-scale, semi-distributed model CatchMODS (Newham et al., 2004). The catchment was divided into 70 subcatchments (spatial units) of about 40 km^2 in size. Each subcatchment comprised a hillslope area and a stream reach. Stream reaches were linked to each other to build up the stream network that defined the catchment with a node-and-link system. Outputs from each reach (i.e. link) to the next were calculated at any exit point (i.e. node).

Hillslope (i.e. sheet and rill) erosion of subcatchment areas was calculated using the Revised Universal Soil Loss Equation (Renard et al., 1996) adapted to Australian conditions (e.g. Lu et al., 2001). The rainfall erosivity factor (R) was estimated using the Lu and Yu (2002) procedure from monthly rainfall data (1950-2005) of the agro-climatic zones of the catchment and ranged from around 600 in the north to 820 MJ mm ha^{-1} h^{-1} a^{-1} in the southern slopes. The soil erodibility factor (K) (0.015-0.045 (Mg ha)[(MJ ha^{-1})(mm h^{-1})$]^{-1}$ was derived from the soil map and Rab et al. (2002) database (Melland et al., 2008). The cover factor (C) was calculated for 15 days intervals as the Soil Loss Ratio of the SOILOSS method (Rosewell, 1993), which is an adaptation of the USLE to Australian conditions. Annual C factors were weighted against 15-day interval rainfall erosivity. Annual C factors ranged from 0.007 under open forest, to 0.18 in annual pastures, to 0.50 in a two-year wheat-fallow rotation. In our study, no detailed land use map was available, but since the 1960s the percentage of land use cover of each agro-climatic zone for decadal periods had been reconstructed from interviews and historical records (Vigiak et al., 2008). Subcatchment C factors were calculated as the weighted average C of the land use cover occurring in each decadal period (1960s -2000s) and agro-climatic zone. The subcatchment weighted C factor was applied to all cells of the subcatchments. The topographic factor (LS) was calculated according to Moore and Wilson (1992) using a 20 m pixel size DEM and averaged across each subcatchment.

Gully erosion sediment loads were assessed on the basis of the extent, connectedness, and dimensions of gullies in each subcatchment (Whitford et al., 2008). The subcatchment SDR was applied only to sediment produced by gullies that were not directly connected to the stream network, i.e. gullies that deposited sediments in large fans far from the stream, which represented 6.5% of the total length of the gully network. In contrast, gullies that were directly connected to the stream network were assigned a SDR of one. Sediment yields due to gully erosion were estimated to range between 0 and 7 t km^{-2} y^{-1}, with an average of 0.7 t km^{-2} y^{-1} (Whitford et al., 2008), representing up to 80% of total sediment loads. In this application, CatchMODS was run at annual time-steps and used to estimate the 10-year average annual sediment loads at subcatchment outlets.

4. SELECTED LANDSCAPE APPROACHES

The following landscape approaches were selected to regionalise the hillslope-scale SDR.

a) Topographic convergence. Mitasova et al. (1996) proposed to use profile curvature (in the downhill direction) and tangential curvature (perpendicular to downhill direction) to account for erosion and deposition along the hillslopes. For each cell of a given grid, deposition ED is equal to:

$$ED = \frac{d(E\cos\alpha)}{dx} + \frac{d(E\sin\alpha)}{dy} \qquad (1)$$

where α is the slope aspect of the grid cell [radiants]; x and y are the cell dimensions [m]; and E is the erosion amounts for that cell [t ha^{-1} y^{-1}]. As we had no cell data on crop cover (C factor), in our application, E was assumed equal to 1 for all cells, therefore equation 1 is a purely topographical index that accounts for erosion and deposition in complex terrain.

b) Sediment transport capacity. Rustomjii and Prosser (2001) proposed that sediment delivery potential for a hillslope to the valley floor depended on the upslope flow accumulation area of the hillslope and the mean gradient of the valley area. Sediment transport to the stream network is written as:

$$q_s = k_1 k_2 (a^{\lambda})^{\beta} S^{\gamma} \qquad (2)$$

where q_s is the sediment transport capacity of a hillslope of area a [m^2]; and S is the gradient of the valley floor [fraction], i.e. the portion of the subcatchment adjacent to the rivers. The parameter k_1 relates to particle size and sediment cohesion, whereas k_2 relates upslope area to runoff generation. Lacking information to change k_1 and k_2 in space, the two parameters together can be seen as one single scaling factor that can be held constant in a given catchment. In our application the product of k_1 and k_2 was assumed equal to one for simplicity. Rustomjii and Prosser (2001) showed that there is considerable evidence to choose $\beta = \gamma = 1.4$. The choice of λ depends on hydrological conditions, and should be < 1 for dynamic Hortonian flow conditions, i.e. where a portion of runoff generated along the slope will not reach the stream, like the semi-arid Avon-Richardson catchment. The suggested λ value for dynamic Hortonian conditions is 0.712, but there is little evidence in literature to guide the choice of this parameter.

c) Travel time. Ferro and Minacapilli (1995) proposed that sediment delivery ratio of a morphological unit to the stream should depend on the travel time t_p of overland flow in the unit:

$$SDR = \exp(-\delta t_p) \tag{3}$$

where the coefficient δ can be considered constant for a given catchment and was set to 1 for simplicity (Bhattarai and Dutta, 2007). The travel time t_p was estimated as the time of concentration t_c of each subcatchment and derived according to the time lag equation of the SCS service (cited in Haan et al., 1994):

$$t_p = t_c = 0.6T_L = 0.6\frac{L^{0.8}(SS+1)^{0.7}}{1900Y^{0.5}} \text{ (for 50 <= CN <= 95)} \tag{4}$$

where L is the hydraulic length of the subcatchment [feet]; SS [mm] is the soil storage capacity estimated with the curve number (CN) method; and Y is the average slope of the subcatchment [%]. The hydraulic length L was approximated as the average length of flow pathways in the subcatchment to the stream network. SS was estimated from the annual weighted CN average of land use and soil categories of the subcatchment. The travel time approach was further developed by Lu et al. (2006), who applied travel times to different particle sized sediments (sand, silt and clay) to calculate regional SDRs.

d) Flux connectivity. Borselli et al. (2008) proposed an index to measure the connectivity between hillslopes and the stream network that has two components. The upslope component represents the potential for down-routing, i.e. the potential for run-on at a given location; the downslope component accounts instead for potential flow sinks between that location and the stream network. The crop factor C of RUSLE is used as a proxy of surface roughness to measure the resistance of runoff to pass through a cell. For any cell y of the catchment, the flux connectivity index is then:

$$I_{c,y} = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) = \log_{10}\left(\frac{\overline{C}\,\overline{S}\sqrt{A}}{\sum_{i}^{n}\frac{d_i}{C_i S_i}}\right) \tag{5}$$

where the denominator depends on the downslope route from cell y to the stream, i.e. the sum for the n cells composing the flow pathway of the ratio between the length of pathway d_i, and the product of C factor of the cell C_i [fraction] times the slope of the cell S_i [fraction]. The numerator depends on surface A [m^2], average slope $\overline{S}$ [fraction] and average factor $\overline{C}$ [fraction] of the area upslope of y. The flux connectivity index is a cell-based algorithm, but again, because no cell land use information was available, C factors were held constant in each subcatchment. Although this approach reduces the power of the index to discriminate between locations along a flow pathway, the effect of large-scale land use changes across the catchment (e.g. grazing versus broad-acre cropping regions) could be assessed.

The selected landscape approaches resulted in four subcatchment landscape distributions to guide SDR regionalisation, although landscape approaches based on cell-based algorithms, i.e. (a) and (d), were first averaged across each subcatchment. Given the heterogeneity of their algorithms, the landscape approaches resulted in very different distributions. Two main transformations were applied to the original subcatchment landscape index distributions. First, subcatchment landscape distributions were normalised into standard scores using the average and standard deviation of the original distribution. Then a sigmoid relationship between landscape index and SDR distribution, as proposed by Borselli et al (2007), was applied, so that the final SDR-index distribution ranged from 0 to 1. Finally, the subcatchment SDR-indices were multiplied by a single value (whole-of-catchment SDR) that best captured the catchment sediment loads, and that was obtained from calibration against observations at the stream gauging stations.

5. RESULTS

The predicted location of major hillslope erosion-prone areas in terms of sediment yields [t km^{-2} y^{-1}] of the catchment differed slightly from the constant SDR pattern with application of landscape-variable SDRs (Figure 2). The highest 10% of hillslope sediments (approx. above 1.5 t km^{-2} y^{-1}; table 1) was mainly located in the southern grazed hills. However, the topographic convergence index showed important contributions of sediments from some of the eastern cropping land too.

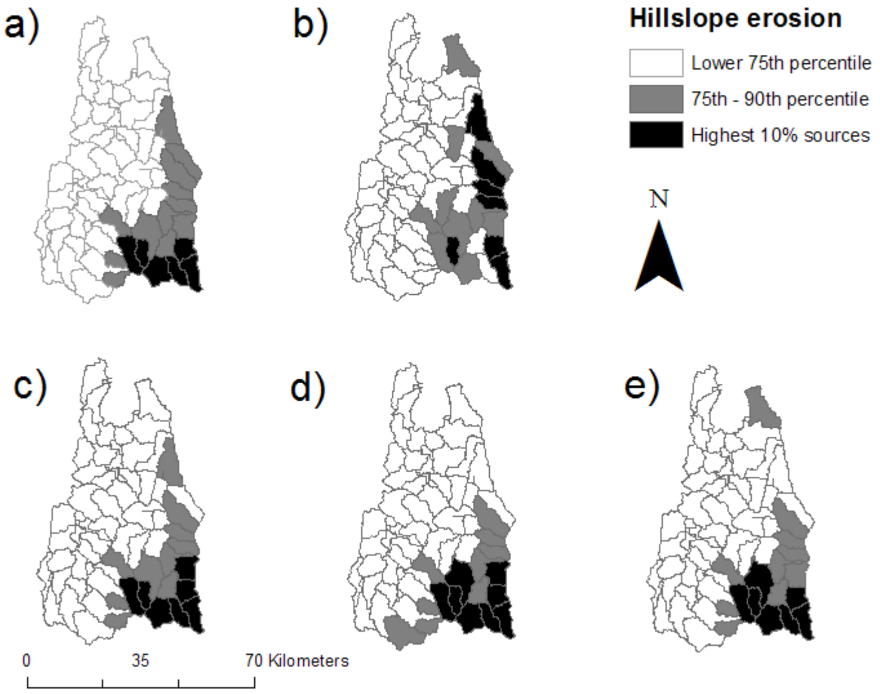

Figure 2. Spatial patterns of hillslope erosion resulting from the application of several SDR distributions: a) spatially constant SDR; b) topographic convergence; c) sediment transport capacity; d) travel time; e) flux connectivity. Grey indicates subcatchment with sediment yields above the 75th percentile; black indicates subcatchments producing the highest 10% of sediment yield (above 90th percentile).

With the exception of the topographic convergence approach, the introduction of a landscape-variable SDR further reduced the amount of sediment contributions from the flatter areas, and emphasised the dominant role of topography on the distribution of hillslope erosion (Figure 3).

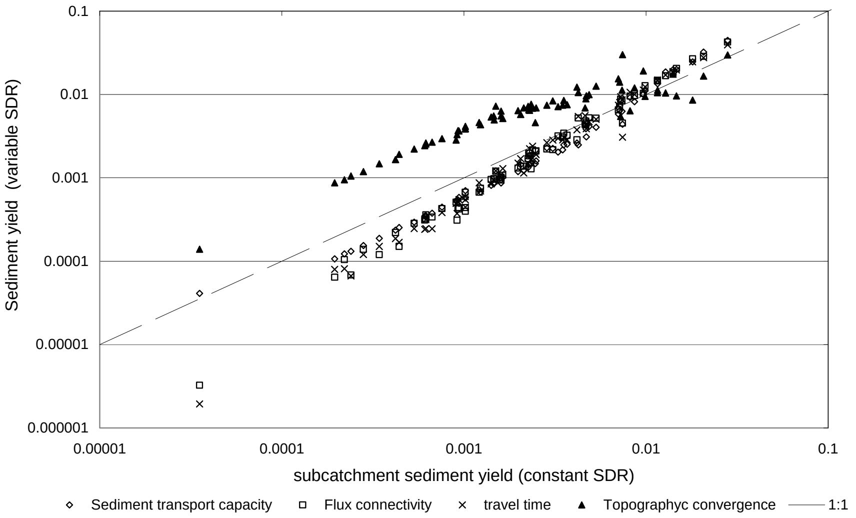

Figure 3. Subcatchment sediment yields [t ha^{-1} a^{-1}] estimated by assuming spatially-variable SDR versus a constant SDR. The dotted line represents the 1:1 sediment yield relationship

Discharge data at the five gauging stations of the catchment was used to estimate decadal average sediment loads (inclusive of gully erosion sources) for 11 period x gauging station observations, against which whole-of-catchment SDR was calibrated. Calibrated SDR, regression equations and Nash-Sutcliffe efficiency of estimated sediment loads against the observations are shown in Table 1. Whole-of-catchment SDR values were very low, ranging from 0.001 to 0.0035, but this was not surprising given the flat topography of the catchment and the important contribution of gully erosion to sediment loads in the southern three gauging stations. SDR values were comparable to Lu et al. (2006) estimations for the Avon-Richardson catchment area, which ranged from 0.002 to 0.08.

6. DISCUSSION AND CONCLUSIONS

The introduction of spatially-variable SDR predicted different spatial patterns of hillslope erosion, affecting the identification of areas where natural resource management should focus. Southern grazed hills were identified as major sources of hillslope erosion sediments; however the topographic convergence approach pattern emphasised the sediment contribution of the flatter areas in the eastern part of the catchment as well.

The ability of some of the landscape approaches to discriminate spatial patterns of sediment delivery was limited by (i) the spatial disaggregation into subcatchments applied to this study, and (ii) the lack of sufficiently detailed land use cover. It was found that the sediment transport capacity and the travel time approaches were the best suited algorithms for applications at the subcatchment spatial scale. This was because they were easy to define at the subcatchment scale and did not require averaging across the subcatchment such as was the case for cell-by-cell algorithms. This conclusion was likely an artefact of the choice of modelling scale applied in this study and may not hold if better spatial data (notably on land use cover for each decade) was available to run models at the cell scale. Future research should explore which approach is most suitable for cell-based applications. The topographic convergence and flux connectivity approaches are probably best suited at cell scale; however, the travel time approach has been applied at cell scale (Bhattarai and Dutta, 2007). The variability of SDR spatial distributions was limited by the transformations applied to the original landscape approaches distributions (Table 1). In particular, the assumption of a sigmoid relationship between landscape normalised distributions and SDR arbitrarily limited SDR variability between 0 and 1 as proposed by Borselli et al (2007). This transformation allowed comparison of the patterns in the absence of field data that would guide the choice of more detailed relationships, but there is no strong field evidence to limit the upper asymptote of the sigmoid function to 1. As SDR depends on the basin area considered (e.g. Ferro and Minacapilli, 1995; Lu et al., 2006), the higher asymptote for SDR might instead be related to the subcatchment area.

Table **1**. Ranges of landscape and SDR indices, calibrated whole-of-catchment SDR, distribution of estimated hillslope erosion, and statistics describing correlations of predicted against observed sediment loads at five gauging stations of the Avon-Richardson catchment (n = 11).

	Spatially-constant	Topographic convergence	Sediment transport capacity	Travel time	Flux connectivity
Landscape index range	n/a	-512; 12	0.17; 5.00	0.32; 0.96	-7.12; -4.57
Normalised SDR-index range	1	0.085; 0.865	0.339; 0.990	0.035; 0.878	0.058; 0.948
Whole-of-catchment SDR	0.00125	0.0035	0.001	0.001	0.001
75th percentile of estimated hillslope erosion (t km^{-2} y^{-1})	0.5	0.5	0.4	0.1	0.5
90th percentile of estimated hillslope erosion (t km^{-2} y^{-1})	1.2	1.5	1.4	1.3	1.5
Regression equation	y=0.98x; $R^2 = 0.67$	y=0.91x; $R^2 = 0.74$	y=0.92x; $R^2 = 0.66$	y=0.92x; $R^2 = 0.67$	y=0.92x; $R^2 = 0.68$
Efficiency	0.61	0.66	0.57	0.59	0.59

The comparison of sediment loads at the five gauging stations (Table 1) did not indicate which pattern best captured sediment source distribution. The number of observations was very small, and three of the five gauging stations are located immediately downstream of areas of active gully erosion, whose sediment contribution (about 80%) was basically independent from the SDR choice. Furthermore, the contribution of the north-eastern part of the catchment, which resulted in the highest variability of SDR distributions, was not monitored.

This study highlighted the need for further research, particularly (i) to define the relationship between landscape indices and SDR with an appropriate and general model; and (ii) to compare the spatial patterns of Figure 2 with field evidence of spatial distribution of erosion and deposition. Point data, such as that provided at gauging stations, offer limited information on the upstream contribution areas, especially where gully or stream bank erosion sources may be dominant. Investigations using e.g. hillslope sediment tracing techniques should be considered in addition to more traditional approaches to hillslope erosion monitoring.

ACKNOWLEDGMENTS

We are very grateful for the input of Dr Anna Roberts and David Tongway to the project. We are also indebted to Lindsay Ezard for his generous contributions, particularly sharing his wealth of knowledge of the Avon-Richardson catchment.

REFERENCES

Abdi, H. (2007). The Kendall rank correlation. In Salkind, N.J., Encyclopedia of measurement and statistics. Sage publications, Thousands Oaks, Canada, 1416 pp.

Bhattarai, R., and Dutta D. (2007). Estimation of soil erosion and sediment yield using GIS at catchment scale. *Water Resources Management*, 21, 1635-1647.

Borselli, L., Cassi, P., Salvador Sanchis, P., and Ungaro F. (2007). Studio della dinamica delle aree sorgenti primarie di sedimento nell'area pilota del bacino di bilancino: progetto (BABI) –Relazione Attività di Progetto. Autorità di Bacino del Fiume Arno, Firenze, Italy, 110 pp (in Italian), [http://www.adbarno.it/rep/babi/Relazione_Progetto_BABI.zip]

Borselli, L., Cassi, P., and Torri, D. (2008). Prolegomena to sediment and flow connectivity in the landscape: a GIS and field numerical assessment. *Catena*, 75, 268-277.

Ferro, V., and Minacapilli, M. (1995). Sediment delivery processes at basin scale. *Hydrological Sciences*, 40, 703-717

Haan, C.T., Barfield, B.J., and Hayes J.C. (1994). Design hydrology and sedimentology for small catchments. Academic press, 588 pp.

Letcher, R.A., Jakeman, A.J., Merritt, W.S., McKee, L.J., Eyre, B.D., and Baginska B. (1999). Review of techniques to estimate catchment exports. *Technical Report EPA 99/73*, Environmental Protection Agency of New South Wales., Sydney, 139 pp.

Lu, H., and Yu, B. (2002). Spatial and seasonal distribution of rainfall erosivity in Australia. *Australian Journal of Soil Research*, 40, 887-901

Lu, H., Gallant, J., Prosser, I.P., Moran, C., and priestley, G. (2001). Prediction of sheet and rill erosion over the Australian continent, incorporating monthly soil loss distribution. Techincal report 13/01. CSIRO Land and Water, Canberra, 40 pp.

Lu, H., Moran, C.J., and Prosser, I.P. (2006). Modelling sediment delivery ratio over the Murray darling Basin. *Environmental Modelling and Software*, 21, 1297-1308

Melland, A.R., Vigiak, O., Rattray, D., Ridley, A., and Whitford, J., (2008). Assembling soil parameters for the HowLeaky? water balance and erosion model. In, Soils 2008: Australian and New Zealand Joint Soils Conference. NZSSS, Palmerston North, New Zealand, 1-5 Dec 2008, 273.

Mitasova, H., Hofierka, J., Zlocha, M., and Iverson, L.R. (1996). Modeling topographic potential for erosion and deposition using GIS. *International Journal of GIS* 10, 629-641

Moore, I.D., and Wilson, J.P. (1992). Length-slope factors for the Revised Universal Soil Loss Equation: simplified method of estimation. *Journal of Soil and Water Conservation*, 47, 423-428

Newham, L.T.H., Letcher, R.A., Jakeman, A.J., and Kobayashi, T. (2004). A framework for integrated hydrologic, sediment and nutrient export modelling for catchment scale management. *Environmental Modelling and Software*, 19, 1029-1038.

Rab, A., Smith, C., and Rees, D. (2002). The 1:250000 Statewide Soil Attribute Coverage Documentation. In. Department of Natural Resources and Environment, Government of Victoria, Centre for Land Protection Research, Epsom, Victoria.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C. (1996). Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). U.S. Department of Agriculture, Agriculture Handbook 703, Tucson, 404 pp.

Rosewell, C.J. (1993). SOILOSS a program to assist in the selection of management practices to reduce erosion. Technical handbook 11, NSW Soil Conservation Service, 92 pp

Rustomji, P., and Prosser, I.P. (2001). Spatial patterns of sediment delivery to valley floors: sensitivity to sediment transport capacity and hillslope hydrology relations. *Hydrological Processes*, 15, 1003-1018.

Vigiak, O., Newham, L., Rattray, D., Melland, A., Ridley, A., Whitford, J., and Croke, B. (2008). Hydrological scaling for predicting catchment response to land management changes. In Bruthans, J., Kovar, K., and Hrkal, Z. HydroPredict'2008 Predictions for hydrology, ecology, and water resources management: using data and models to benefit society, Prague, 15-18 September 2008, 315-318.

Whitford, J., Vigiak, O., Newham, L.T.H., Melland, A., and Ridley, A. (2008). Estimating activity of gully erosion in central Victoria for catchment modelling of water quality impacts. In, Soils 2008: Australian and New Zealand Joint Soils Conference. NZSSS, Palmerston North, New Zealand, 1-5 Dec 2008, 272)