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

Using geoprocessing tools to model the potential impact of landcare on the spatial pattern of sediment delivery

J. Newby and D.V. Pullar

University of Queensland, Australia
Email: d.pullar@uq.edu.au

Abstract: Geoprocessing tools are now commonly used in GIS to develop custom geographic applications. While GIS technology needs to advance further in its support for time-based processes and parameter estimation, it is possible to build simplified physical process models by integrating component geoprocessing tools. The advantage is that custom built environmental applications are more flexible and scalable to problem requirements. This paper reviews, by way of an application, a geoprocessing tool for hydrological modelling; namely terrain analysis using digital elevation models (TauDEM). TauDEM is a set of tools for terrain analysis, including analysis of patterns of erosion and deposition in a watershed. We analyse a watershed in the Philippines to examine how sediment laden overland flows are routed through the landscape. The purpose is to determine if the location and intensity of landcare practices at a catchment scale can significantly reduce the sediment delivery to downstream areas. We briefly describe the geoprocessing functions in TauDEM and use these to examine the influence of changing land management practices. We find that spatially targeted soil conservation practices can achieve reduction in sedimentation for lower levels of adoption.

Keywords: *DEM, GIS, Terrain analysis, Geoprocessing, Hydrological modelling*

1. INTRODUCTION

GIS has a long tradition of integration with hydrological modelling (Martin et al., 2005). This typically has involved a loosely coupled integration between GIS and hydrological software, where the GIS performs data pre-processing and visualisation. This approach works but there are drawbacks: i) the interface is typically dedicated to a hydrological model with specific data needs and program control, and ii) the software cannot be easily integrated with other GIS technology. Buehler and McKee (1998) put forward a vision of open integration with geoprocessing tools as re-usable components to more flexibly built environmental applications. Ideally this would bring about progress in GIS data models (representations and analysis capability) to better support environmental process modelling. Hydrological applications require support for time domain along with a spatial representation for material flows and balancing flux over a control surface (Maidment, 1996). Even today there are few examples of this level of integration. Some software toolkits are available with these features (Argent et al., 2005) but there are few implementations available in GIS.

This paper reviews, by way of an application, a geoprocessing tool for hydrological modelling; namely terrain analysis using digital elevation models (TauDEM). TauDEM is a set of tools for terrain analysis, including analysis of patterns of erosion and deposition in a watershed (Tarbotton, 1997; 2003). We analyse a watershed in the Philippines to examine how sediment laden overland flows are routed through the landscape. Our goal was to assess the relative impact of soil conservation practices by changing key parameters in a hydrological model. We refer to this in the paper as modifying the location and intensity of landcare adoption practices without specifically naming the practice. A related paper by Newby and Cramb (2009) provides details on specific practices and their economic implications for the study area. A significant question was if sedimentation in irrigation channels and dams in the lower part of the catchment are affected by erosion from farming in the upper part. We briefly describe the geoprocessing functions in TauDEM and use these to examine the influence of changing land management practices.

2. GEOPROCESSING FUNCTIONS FOR HYDROLOGICAL MODELLING

It is possible to build simple hydrological models to address a range of problems in GIS by combining general geoprocessing functions with specialised terrain analysis functions (Gallant and Wilson, 2000). A raster DEM is almost universally accepted as the most flexible representation of surfaces. It supports a uniform data structure that can be efficiently manipulated. However there are some drawbacks; rasters have a fixed cell resolution which is not adaptive to terrain variability at different landscape scales. The raster is amenable to hierarchical aggregation with pyramids, but a regular decomposition of space is not sufficiently adaptive for terrain analysis. Therefore data representation is still a challenge and limits geoprocessing to describe environmental patterns and processes (Deng et al., 2008).

Two important raster geoprocessing functions for extracting surface flow topography are: i) the local drain direction, and ii) flux accumulation (Burrough and McDonnell, 1998). These functions are a common precursor for delineating drainage networks in GIS, but there is a distinction in the precision with which algorithms compute flow. The simplest algorithm computes flow for 8 cardinal directions (D8) and more precise algorithms compute continuous flow directions (D∞). TauDEM supports either method, but the later gives superior results. The local drainage direction is extremely useful for calculating flow properties and drainage connectivity. This is derived for each cell by examining the drainage directions of neighbouring cells and counting those that drain to it. For D8 this is trivial as there is a one-to-one relation between a supply cell and a receiving cell, i.e. it flows to a neighbour along one of the 8 directions. For the D∞ there is a one-to-many relation between a supply cell and receiving cells, and the flow needs to be proportioned to the appropriate receiving cells (Tarboton, 1997).

Flux accumulation is computed by summing the drainage contribution over all cells following a drainage order, i.e. from ridges to outlets. The result is that each cell sums the upstream elements draining to it. This is useful for calculating surface flow properties for the contributing area, water flows and erosion processes. Burrough and McDonnell (1998) provide a simple explanation of the way mass balance for each cell accounts for water and material fluxes. The general form for mass flux is: $flux_{\Delta t}$ = mass $in_{\Delta t}$ – mass $out_{\Delta t}$. Changes in a cells water storage over a time step Δt may be described in terms of: i) vertical components (precipitation, infiltration, interception and evaporation), and ii) lateral components (inflow, outflow). The net balance for vertical flux is computed from cell properties, but lateral flux requires calculations based upon accumulated flows. A large part of hydrological modelling is concerned with describing the rates of flow and balancing the net flux over a landscape. We are interested in how accumulated flux is handled in

GIS by: i) static, and ii) dynamic geoprocessing function. A static function sums cell values without accounting for changes in values over the calculation. For instance, the accumulated flux for cell area is static and gives the contributing area for each cell. It is possible to compute other static indices for hydrological potential, such as a topographic wetness index, but the more interesting hydrological qualities require a dynamic calculation. A dynamic function accounts for changes in state for values summed by accumulated flux, i.e. the vertical and lateral components of flux referred to above. Dynamic models may also include an explicit time step. For instance, water storage is affected by infiltration rates and inflow/outflow rates. A dynamic calculation of accumulated flux is also important for erosion processes. For instance, if the transport capacity of flow is sufficient it will move eroded material to a downslope cell, otherwise if outflow is less than inflow then deposition occurs in a cell.

The advantage of TauDEM for hydrological modelling is that it uses the D∞ algorithm and supports dynamic calculation of accumulated flux. The description for these and other hydrological analysis functions may be found at the web site http://hydrology.neng.usu.edu/taudem/, but a brief description of the D∞ flow direction and accumulated flux geoprocessing functions are:

i) *Dinf Flow Directions*: Input is the DEM and flow paths. The function proportions flow to the two downslope cells (i.e. a continuous flow direction is divided between the component axes for the two receiving cells). It expects the input DEM is hydrologically conditioned (i.e. pit filled), and the flow paths have verified stream connectivity (i.e. flow paths from edge cells to outlet cells).

ii) *Transport Limited Accumulation*: Input is the D∞ flow directions, erodible soil supply, transport capacity, and outlets. The output is the transport flux and deposition. This function accumulates the flux of eroded material constrained by what can be transported due to flow. The transported material is limited to either a combination of the erodible soil E_{soil} plus inflows ΣT_{in}, or to the transport capacity T_{cap}. This is expressed as the cumulative transported material $T_{out} = \min(E+\Sigma T_{in}, T_{cap})$. The net flux T_{flux} is then the difference $T_{flux} = \Sigma T_{in} - T_{out}$, and deposition is $D = E + T_{flux}$.

The transport limited accumulation can be used in a variety of ways over a time series or lumped time scales to derive event-based or indicator-based process models. Depending on the process being modelled different inputs are computed for the eroded soil material and transport capacity. For example, an indicator-based process model would compute available eroded soil material from a universal soil loss equation, and the transport capacity from a function of land cover, flow volume and slope. While beyond our needs, an event-based model can equally be developed with the transport limited accumulation function by simulating time step iteration with more refined formulations for erosion and transport capacity. The next section will describe our application of TauDEM for an indicator-based process model.

3. APPLICATION OF GEOPROCESSING FOR A CATCHMENT MODEL

We developed a simple hydrological model to describe the relationship between land management practices and soil erosion for the Inabanga Watershed in the Philippines. The catchment is located in an area with high rainfall, mountainous terrain, and intensive agricultural activities. Land is being degraded, and agricultural production has declined, due to intensified crop farming. Newby and Cramb (2009) pose a possible solution to identify priority areas for soil conservation, and to see what effect soil conservation practices have on soils and farm productivity. In particular there is concern sedimentation will affect the functioning of irrigation channels and the catchment dam will need to be rebuilt. Hence the application is mainly sensitive to sediment delivery as opposed to soil loss.

We analysed patterns of land management practices in GIS to see what effect this had on soil erosion. The data sets available included: i) a 30m DEM derived from SRTM, ii) land cover maps derived from Landsat-7 ETM+ imagery, iii) 1:500,000 soil map classes, and iv) short term field observations of weekly rainfall, runoff and soil loss on sites covering the main land cover classes. Hence we have reasonably good broad mapping data, but sparsely sampled hydrological data. None the less our objective was to analyse the relative impact of practices and it was not necessary to make accurate predictions. A simplified indicator-based model was sufficient to understand how patterns of land management practices would affect soil erosion. The two inputs to be derived, and changed in relation to land management practices, are soil erosion supply and transport capacity.

3.1. Soil erosion supply

The upland catchments of the Philippines have soil profiles ranging from relatively deep acid soils to the shallow calcareous profiles that dominate much of the upper Inabanga catchment. The soil mapping was too course to infer differences in soil erodability factors, so we assumed a uniform soil supply layer and tested its sensitivity with a couple of values. Erodability soil supply values of 3 tonnes and 10 tonnes per cell (30m raster) were used. This equates to approximately 111 tonnes per hectare or around 9mm of soil loss, using a bulk density of 1.2. The total supply at a given cell will equal the sum of this local supply plus the flux coming into the cell from its contributing neighbours.

3.2 Transport capacity

Transport capacity was calculated from the data on overland discharge and slope. Prosser and Rustomji (2000) give a generic equation for hillslope sediment transport capacity as:

$$q_s = k\, q^{\beta}\, S^{\gamma} \qquad (1)$$

where: q_s is sediment transport capacity per unit width of slope;
q is runoff flow per unit width;
S is the surface gradient; and
k, β and γ are empirical or theoretically derived coefficients.

The k coefficient is determined from landscape characteristics, in our study we used surface roughness factors based upon land cover. In the absence of experimental data on surface roughness we used published coefficients from studies conducted in tropical climates, Table 1 shows the values.

Table 1. Land use cover factors used in the Transport Capacity derivation

Land use classification	Cover factor
Forest land	0.06
Rice land	0.28
Shrub land	0.2
Agricultural land	0.5
Bare soil	0.5
Built area	0
Water	0
Grassland	0.01

Likewise the power terms in Eq. 1 are based on values reviewed by Prosser and Rustomji (2000). In the absence of better knowledge, they suggest using the median parameter values ($\beta = \gamma = 1.4$).

The runoff flow parameter in Eq. 1 has a significant impact on the determining whether a cell receives net deposition or net erosion. During peak flow events the transport capacity of a cell may increase to the point that it becomes supply constrained. This means that the sum of the locally eroded solid and incoming transported soil will all be routed to neighbouring cells. Alternatively, in less intensive rainfall events a cell may be transport capacity constrained, meaning that the cell does not have the capacity to move soil to the next cell, resulting in deposition in that cell.

Genson (2006) monitored areas covering the different land cover types in upper Inabanga Watershed. The highest weekly rainfall varied between the gauging stations from 355 – 703mm. Genson found that over 95 per cent of the total amount of soil loss from both agroforestry and maize fields occurred during those weeks of above 60mm of rainfall, or from 2 weeks over the 98 week observation period. Table 2 summaries the maximum weekly and total rainfall, runoff and soil erosion at the field sites.

Table 2. Rainfall, runoff and soil loss (Genson, 2006)

	Agro-forestry	Maize	Forest land	Grass land	Oil palm
Max. weekly rainfall (mm)	355	461	355	355	703
Max. weekly runoff (mm)	68.4	344	9.5	296	149
Rainfall (mm)	3850	4515	3850	4515	5044
Runoff (mm)	694	1311	13	952	265
Soil loss (t/ha)	4.3	79.9	0.4	12.1	4.9

The final variable in Eq. 1 is runoff flow. Early attempts to develop a water budget and derive runoff flow gave misleading results, most likely due to poor data and poor understanding of runoff processes. Therefore we decided to assume base values that were consistent with field data from Genson (2006). A range of values were used to test sensitivity, these included weekly runoff flow rates of 50, 100, 250, 500, and 1000.

3.4 Analysis and results for erosion modelling

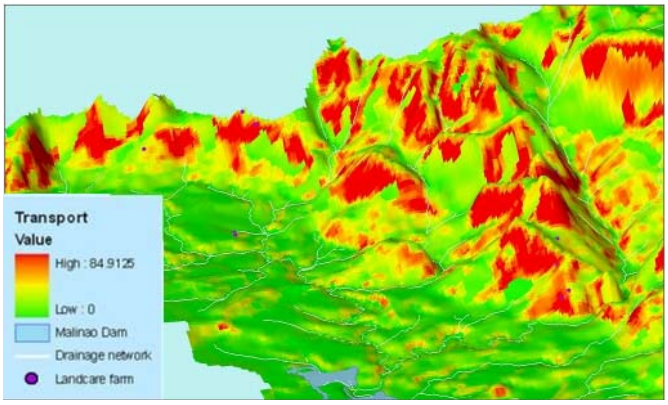

Figure 1. Pattern of sediment transport (Runoff flow = 100)

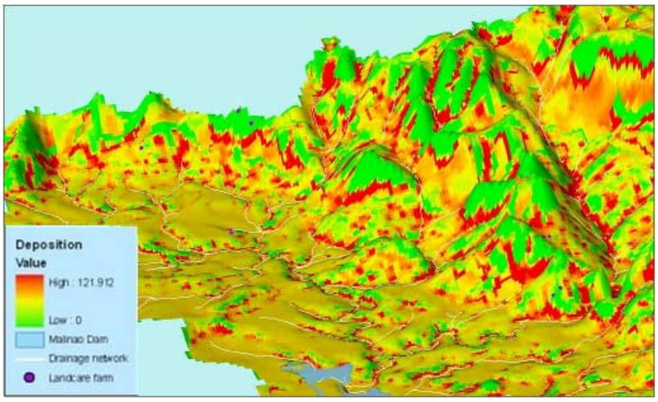

Figure 2. Patterns of deposition (Runoff flow = 100)

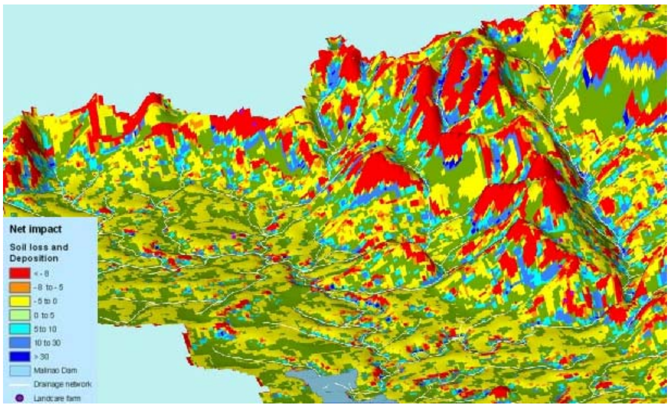

Figure 3. Areas of erosion and deposition with current land use (Runoff flow = 100).

The assumptions made for model parameters meant that results could only be used in a predictive sense, but they were adequate to test the impact of changes in adoption of soil and water conservation practices. To gain confidence from model results we tested the sensitivity of model parameters by modifying the land cover factor in Table 1. The results for sediment flux, deposition and erosion are shown in figures 1, 2 and 3. Note that the primary focus was on sediment delivery as this had the largest economic implication for lost irrigation activity and replacing the catchment dam, however soil loss was always a close secondary consideration.

Figure 1 illustrates those cells with large amounts of sediment transport, whilst Figure 3 shows the combined net erosion and deposition. As can be seen, deposition largely occurs at the bottom of hillsides and along the drainage network. The runoff flow parameter has a large impact on the results. Tests show that lower values for runoff are more sensitive on mid-slope areas, and higher runoff values are more sensitive to erosion on the upper slopes and deposition on drainage lines.

As a crude example of a modelled scenario we changed all the agricultural land cover types in the catchment to shrub land, i.e. the land cover factor for agriculture was changed from 0.5 to 0.2 as per Table 1. We re-ran the sediment flux accumulation geoprocessing tool for the five different runoff values and compared the results for total deposition along the stream network. The changes for one runoff value are shown as a map in Figure 4, and all runoff values are summarised in Figure 5. We only present relative changes as the results are not true predictions. But given this assumption, useful information can be inferred from the results depicting patterns of stream sedimentation.

From Figures 4 and 5 we see that as the flow level increases the absolute reduction in sediment reaching the drainage network also raises. However, at increasing flow the relative reduction as a percentage of total delivery falls. That is, given that the target area is only a small percentage of the total watershed, at high flow levels there will be large amounts of sediment coming from regions beyond the interventions potential control. The next section presents more interesting scenarios for land cover changes resulting from largetted landcare programs.

3.5 Impacts of landcare adoption

The model hypothesis was that adoption of landcare programs is more effective if targeted at locations at higher risk of erosion. In the past landcare programs had no spatial prioritisation, so a spatially targeted strategy would

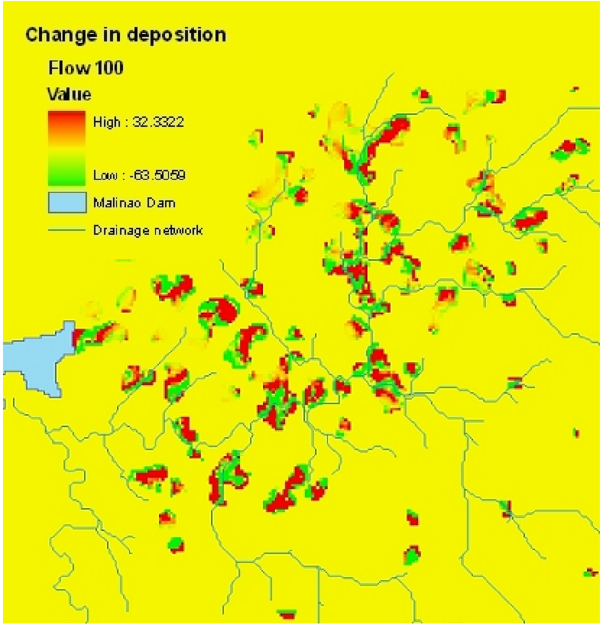

Figure 4. Change in deposition as a result of land cover change of agriculture to shrubs.

require local interventions. For instance, for farmers to construct natural vegetative strips along the contour or to integrate agroforestry within the farm system. Improving land practices was tested in a hypothetical way (i.e. tests were not at this stage associated with a specific land practice) by changing model parameters; in particular the land cover factor used for sediment transport. In essence we modify the flow characteristics to see the impacts on erosion in the following ways:

i) reduction at random locations in watershed,
ii) reduction at targeted areas showing higher erosion risk for different conditions,
iii) reduction at areas with erosion risk and within or near riparian areas.

The results of different levels of reduction as related to the cover parameter for sediment capacity are shown in Figure 6. Simulations were run for a variety of parameter combinations, but they show a similar pattern for results. The random adoption of landcare practices had a linear relationship to reducing river sediment deposition, but was consistent over different parameter combinations. The more selective adoption scenarios show reductions for lower levels of adoption. For targeted adoption this is pronounced at lower flow values, and less pronounced at higher flows. For river targeted adoption it was pronounced for all levels of flow regimes.

Targeting areas with the highest amount of sediment flux produces a more than proportional impact at low runoff flow values. As the flow value increases the strategy becomes progressively less effective. At low level of adoption the strategy may be less effective than the random process of adoption. This is because at higher flow levels, steep sloping cells become increasingly supply limited. That is, the combination of the high flow and steep slope dominates the transport capacity value for the cell, with almost the entire sediment flux passed onto the neighbouring cells regardless of land use. It is only when this flux reaches flatter land that the flux may become limited by the transport capacity and be deposited. However, at high flow levels this may not occur before the flux makes it to the drainage network and ultimately delivered to the dam.

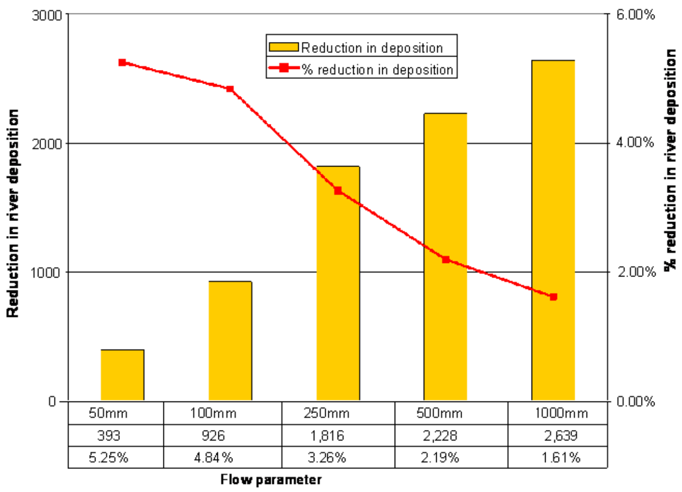

Figure 5. Impacts of land use change of sediment deposited in drainage network

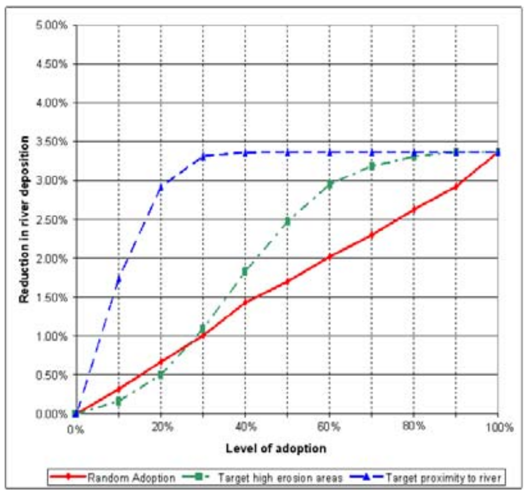

Figure 6. Impacts of flow reductions for adoption strategies: i) random, ii) targeted, and iii) close to rivers. Supply of 10mm of soil and runoff flow parameter 100.

4. CONCLUSION

The paper has reviewed the use of geoprocessing functions in GIS for hydrological modelling. This review was motivated by an application in the Philippines to assess the impacts of adoption of landcare and soil conservation practices for upland rural areas. The modelling shows there are significant local impacts in erosion based upon the level of adoption and spatially targeted interventions, but this had little effect on regional concerns such as sedimentation in the lower parts of the catchment and dams. Numerous filters and sinks exist between the upland plots where adoption is taking place, and the drainage system that delivers sediment to the Malinao Dam. Further discussion of the economic implications of adoption may be found in Newby and Cramb (2009). The project had sparse data that would normally make hydrological modelling difficult, but a general understanding of the processes was deemed more important than accurate predictions. Many of the advanced hydrological models were too complex or had demanding data requirements for our purposes. The use of geoprocessing functions was found to be flexible and easy to tailor to our needs. In particular, the geoprocessing tool for flux accumulation was a good building block to model sediment erosion, and allowed us to derive suitable inputs from our own conceptual model for sediment transport and with the available data. Being able to break a problem down in GIS and build up solutions from geoprocessing functions leads to more scalable solutions, and component integration to build more complex systems, such as decision support tools. In our case we were able to experiment with different model parameters to explore management scenarios. Two other notable GIS's that offer this capability include PCRaster (De Roo et al., 2000) and GRASS (1996).

An application of the geoprocessing tool is given for a hydrological model, the aim is to show that under similar flow and supply characteristics that the location of adoption within the landscape influences offsite impacts. Results show that the position of adoption within the landscape is often more important than the level of adoption. It is possible to more strategically target adoption in particular areas using the full suite of policy tools. The current research is on the costs and benefits of adoption with strategic landscape targeting.

5. REFERENCES

Argent, R. M., Grayson, R. B., Podger, G.D., Rahman, J.M., Seaton, S., and Perraud, J-M. (2005) E2 – A flexible framework for catchment modelling, *Proc. MODSIM Conf.*, Dec., Melbourne, Australia.

Buehler K., and McKee, L. (1998) *Introduction to Interoperable Geoprocessing and the OpenGIS Specification*. Open GIS Consortium Technical Committee, June 3.

De Roo, A.P., Wesseling, C.G. and Van Deursen, W.P. (2000), Physically-based river basin modelling within a GIS: The LISFLOOD model. *Hydrological Processes* 14, 1981–1992.

Deng, Y., Wilson, J.P. and Gallant, J.C. (2008) Terrain analysis. In: J.P. Wilson and S. Fotheringham (Eds.), *The Handbook of GIS*, 417-433.

Gallant, J.C. and Wilson, J.P. (2000) Primary topographic attributes. In: J.P. Wilson and J.C. Gallant (Eds.), *Terrain Analysis: Principles and Applications.* New York, John Wiley and Sons, 51-86.

Genson, I.C. (2006) *Erosion and water resources assessment in the Upper Inabanga Watershed, Philippines: application of WEPP and GIS tools*. University of Western Sydney. School of Natural Sciences, Sydney, Australia.

Maidment, D.R. (1996) GIS and Hydrologic Modeling—an Assessment of Progress. In: *Proc. 3rd Int. Conf. on Integrating GIS and Environmental Modelling*, CD-ROM. National Center for Geographical Information and Analysis, Santa Barbara, CA.

Martin P.H., LeBoeuf E.J., Dobbins J.P., Daniel E.B., Abkowitz M.D. (2005), Interfacing GIS with water resource models: a state-of-the-art review. *Journal American Water Resources Association* 41(6), 1471–1487.

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

Newby, J.C. and Cramb, R.A. (2009) Living on the margin: Assessing the economic impacts of Landcare in the Philippine uplands. *Australian Agricultural and Resource Economic Society Conference*, Feb., Cairns, Australia.

Tarboton D.G. (1997) A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water Resources Research* 33(2), 309–319

Tarboton D. G. (2003) Terrain Analysis Using Digital Elevation Models in Hydrology, *23rd ESRI International Users Conference*, San Diego, California, July 7-11.