Representative Hillslopes in Geospatial Modeling: Representing Environmental Properties and Processes at Various Scales

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Abstract

Spatial analysis and modelling tools in GIScience have limitations in accurately representing environmental properties and processes at various scales. Often the way environmental data was gathered, processed, and modelled in the digital domain is insufficient to represent the true natural temporal and spatial variability. This research is an attempt to implement a newly developed data scaling scheme in a GIS and Environmental Modelling setting that consequently track the flow and optimize the transfer of information by minimizing uncertainty in the digital domain. Our case study is a process-based, continuous, spatially distributed runoff and soil erosion modelling approach for the semiarid rangeland environment of the Lucky Hills Watershed in Arizona. The Water Erosion Prediction Project (WEPP) model is a representative hillslope and watershed model that requires the aggregation of spatial information before a model run. As an alternative, we have developed two simulation methods that enable taking advantage of more spatially detailed information about the terrain. However, it has to be determined, if we necessarily achieve better results in using either of the three model simulations. The experience of coordinating scaling theory, implementation procedure, and application indicate that Data Collectors, GIScientists, Modellers, and Decision Makers have to effectively communicate and understand the importance of aggregating and disaggregating information to validate and produce useful simulation results.

1. Introduction

There are certain limitations in the data formats used in GIScience and its tools representing environmental properties and processes accurately. With the latest methods in data gathering methods, we achieve more and more detail in representing environmental properties at a particular scale, but are still unable to use these detailed information to predict landscape processes at various spatial and temporal scales. These issues become apparent when we try to develop decision support tools to predict overland flow generation, soil erosion and deposition on hillslopes and channels in small watersheds (Renschler and Harbor, 2002).

Models to predict water and sediment budgets can be rather simple: even a one-dimensional vertical water flow model (Figure 1) for a single point in the landscape can be used effectively to predict regional water balances (Bormann, et al., 1999). Adding more dimensions to the representation of processes in the model will allow e.g. representing the complexity of converging and diversion of flow in small watersheds (Figure 1).

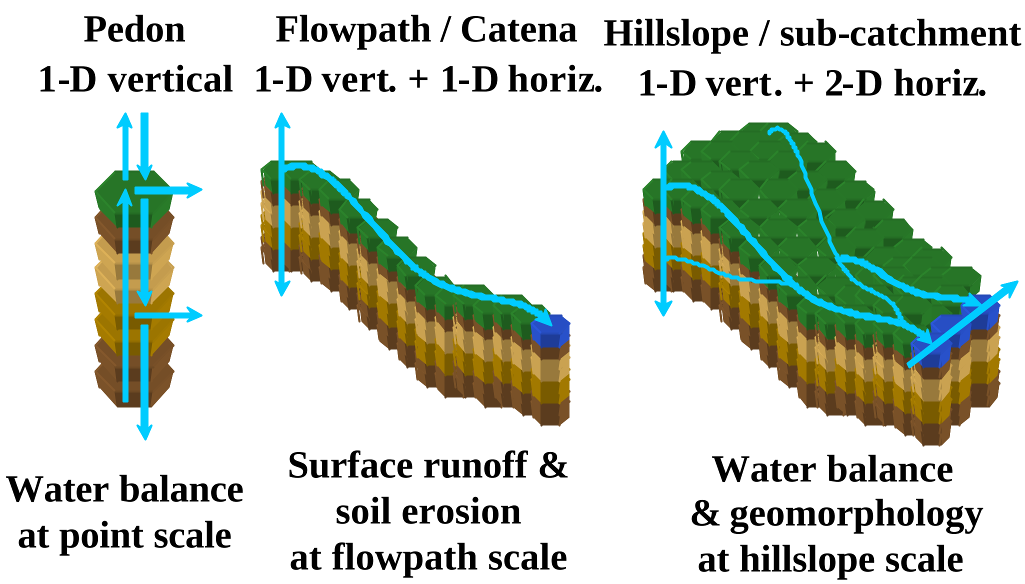


Figure 1. Three different model concepts to simulate landscape processes.

The state-of-the-art Water Erosion Prediction Project (WEPP) model uses a number of input parameters to predict the amount of erosion on flowpaths in a landscape and non-diverting flow in small watersheds (Flanagan and Nearing, 1995). The model has not been used in the past at its capacity due to the challenges in deriving all its model input parameters. The Geospatial interface for the WEPP (GeoWEPP) is a GIS-based wizard assisting the WEPP user to automatically derive the required profiles for hillslopes representing the topography and environmental conditions of each contributing area to a channel segment within a watershed (Renschler, 2003; Renschler et al., 2002). Such representative hillslopes consist of a sequence of Overland Flow Elements (OFE) with homogenous combination of climate, soil, and land use/cover. The delineation of a drainage network and contributing areas to channels segments in GeoWEPP are based on the algorithms of the TOPAZ digital landscape analysis system (Garbrecht and Martz, 1997; Martz and Garbrecht, 1999).

The paradigm of representative modelling units in our case deals with several key questions: Do these representative profiles accurately represent the environmental properties and processes at each of the hillslopes? The representation would be adequate if the lateral topography in flow direction, soil type characteristics, and the vegetation/surface conditions were the same for the entire length of a hillslope. But how do we prepare the model input in a complex topography, different soil types, and various types of land management at the same hillslope? One is faced with the challenge to either represent the environmental properties of the hillslope accurately for the purpose of an on-site assessment (hillslopes) or to represent effectively the processes to assess the off-site impacts (contribution from hillslopes into channels). Is there a single correct representation that can provide valid input and output for both assessment methods? Renschler (2003) developed a scaling theory that allows us to investigate various representations of properties in the model input (different scales of resolution and detail) and evaluate various validation methods of the effective process representation of the model predictions (Figure 2).

PROCESS SCALE	TRUE PROCESS SCALE AND VARIANCE
⇓ *BASIC SCALING* ⇓	ß **MEASURING** ß
MEASUREMENT SCALE	*Observation Unit (measurement device)*
⇓ *1^{ST} SCALING* ⇓	ß **PRE-PROCESSING** ß
DATABASE SCALE	*Common Database Unit (data availability)*
⇓ *2^{ND} SCALING* ⇓	ß **DISCRETIZATION** ß
MODELING SCALE	*Modeling Unit (model requirements)*
⇓ *3^{RD} SCALING* ⇓	ß **MODELING** ß
PREDICTION SCALE	*Prediction Unit (model design)*
⇓ *4^{TH} SCALING* ⇓	ß **POST-PROCESSING** ß
ASSESSMENT SCALE	*Scale of Interest (user requirements)*
⇓ *5^{TH} SCALING* ⇓	ß **EVALUATING** ß
VALIDATION / MEASUREMENT SCALE	*Observation Unit (measurement device)*
⇑ *BASIC SCALING* ⇑	Ý **MEASURING** Ý
PROCESS SCALE	TRUE PROCESS SCALE AND VARIANCE

Figure 1. Scaling theory for implementing environmental assessment tools (Renschler, 2003). Note that scaling and evaluation through scaling requires a transformation of information (=>) and within the domain of digital geo-spatial data handling (^^^).

We compared our results from the three different methods to break down hillslopes and channels into representative units and contributing areas. Instead of using only channel segments between drainage network links (current methodology used in GeoWEPP), we run the data preparation and model simulation for each contributing hillslopes into each cell representing the channel. To validate our results, we tested the impact of these three levels of model predictions for spatially distributed soil erosion and deposition in an experimental watershed. Measurements of watershed runoff and sediment discharges are combined with spatially-distributed sediment balance data derived from long-term Cs137 measurements (Ritchie et al., 2005). The approach of multiple representative profiles created by GeoWEPP will allow users to choose the most appropriate levels of detail and allow for a more accurate representation of hillslopes supporting decision-making in natural resource management.

2. Method Used

GeoWEPP has generally two ways to represent and model surface runoff flow in landscapes (Figure 3). The user has to choose between an off-site (sediment yield prediction for representative hillslopes that drain into channel segments and to the watershed outlet) and an on-site assessment method (soil erosion prediction for cells along a flowpath to a channel segment). In contrast to the off-site method, the on-site methods produces a spatial pattern of erosion (by weighing the soil erosion amounts along a flowpath according to the cell's length and contributing areas; see merging flowpaths 1, 2, and 3 merging in cells A,B, and C in Figure 3) but has no channel routing. Therefore the user faces a difficult choice by either aggregating the input information before a WEPP model run (loosing spatial details and using the model appropriately), or aggregating the model results after running the WEPP model (taking full advantage of the detail the landscape is represented in a GIS).

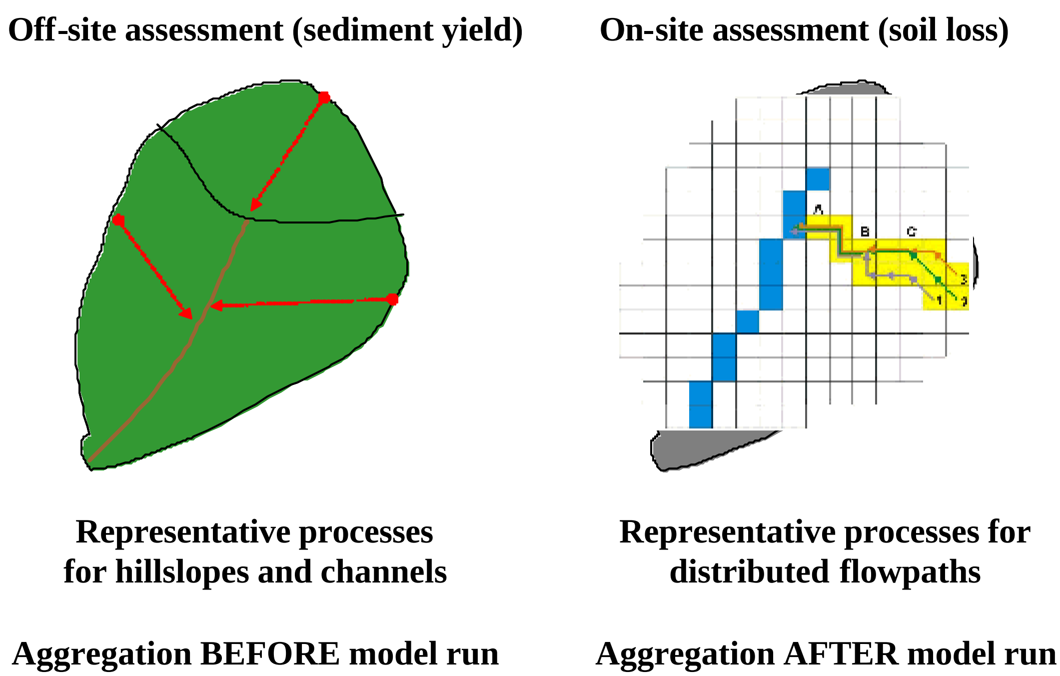


Figure 3. Representation of hillslopes and small watersheds in GeoWEPP.

The current version of GeoWEPP, through the use of TOPAZ (Garbrecht and Martz, 1997), produces subcatchments based on how they drain into each channel of a user-selected watershed (Figure 4). Once these subcatchments are passed to the WEPP model engine, the dominant landuse and dominant soil are used for the input parameters for the hillslope. The problem we face with the current version of GeoWEPP is that the representative profile that is created, along with an aggregate slope, may not be an accurate representation of the hill, especially for more complex subcatchments containing multiple landuse and/or multiple soils mapping units. Even the representative slope of the subcatchment may not depict the varying topography over larger subcatchments.

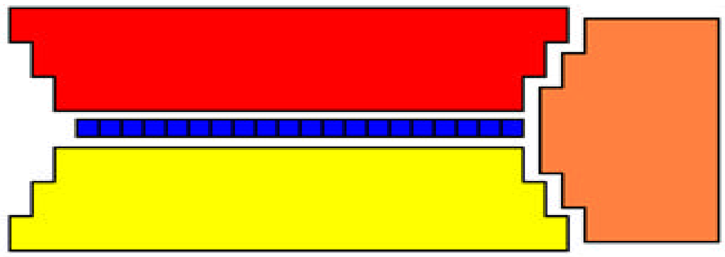


Figure 4. Scheme of three contributing areas of a first order channel segment.

One solution to this problem is to create smaller subcatchments so that they can better represent the watershed being studied. These new smaller subcatchments follow the same theme TOPAZ used to create the larger ones, except that they would be based on how they flow into each individual channel raster cell (Figure 5), not the channel as a whole (as in Figure 3). A Visual Basic program was written to determine the smaller subcatchments based on the information produced by TOPAZ. The program uses several of the output files created by TOPAZ to create a new subcatchment file. The program uses the channel network file, flow vector file, subcatchment file, watershed boundary file to determine how the watershed flows into each channel cell. Figure 5 shows how the subcatchemnts depicted in Figure 4 may have changed.

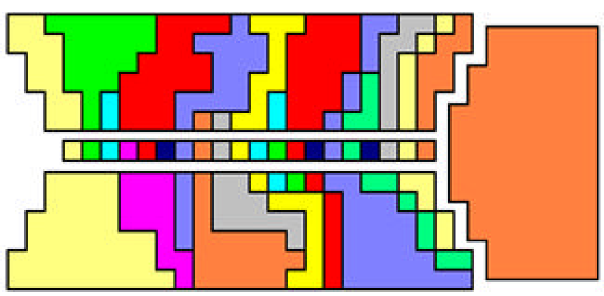


Figure 5. Scheme of contributing areas for multiple cells of a first order channel segment.

Each cell could have zero to three subcatchments flowing into it. In Figure 5, the dark blue channel cells do not have any subcatchments flowing into it, while the first cell of the channel has two subcatchments (right bank and subcatchment). For each channel, the three subcatchments (left, right and source) are remapped so that the number of subcatchments could change from 3 to up to two times the number of channel cells plus one.

3. Study Site

The test site for the validation of the new smaller subcatchment approach is the Lucky Hills watershed within the USDA Agriculture Research Service (ARS) Walnut Gulch Experimental Watershed in southeast Arizona near the town of Tombstone. (Figure 6).

Figure 6. Rangeland Lucky Hills Watershed, Tombstone, Arizona

The data collected from the sample sites within Lucky Hills showed that the erosion and deposition rates ranged from 9.8 t ha^{-1} yr^{-1} (metric tons per hectare per year) of soil loss to 7.0 t ha^{-1} yr^{-1} of soil deposition (Ritchie et al., 2005). The main characteristics of the watershed are shown in table 1.

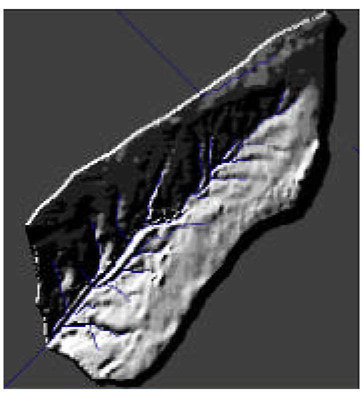
Table 1. Lucky Hills Characteristics (Ritchie et al., 2005)

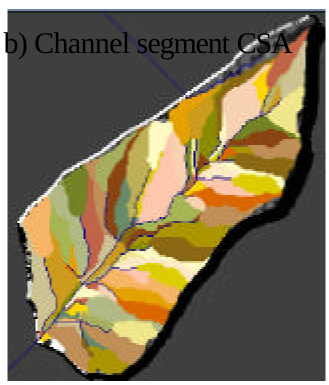
Elevation	1363 to 1375m
Mean Annual Temperature	17°C
Temperature Range	1°C (Jan) to 35°C (June)
Region Precipitation	250 to 500 mm/yr*
Lucky Hills Mean Annual Precipitation	approx 356mm
Soil Type at Lucky Hills (mapped as)	McNeal Sandy Loam (Ustochreptic Calciorthids)
Vegetation	shrub-dominated**

Shrub Height	approx 0.6m
Shrub Cover	about 26%
Clump Leaf Index of Shrubs	1.15 to 1.54

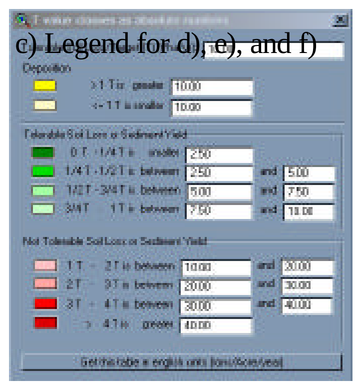
*2/3 occuring in monsoon season (July-August); **Acacia [Acacia constricta Benth.], Tarbush [Floursensia cernua DC], and Creosote [Larrea divaricata Cav.]

A 1-meter DEM of the Lucky Hills watershed was provided by the USDA-ARS (Figure 7a). The DEM was also converted into a 2m, 5m, and 10m DEM using ArcViews Map Calculator and Surface Analysis Tools. The current GeoWEPP version was used to delineate the contributing areas to the various channel segments (Figure 7b). The different DEMs were used to create soil and land cover layers at each of the resolutions. There is no spatial distribution of climate, soil and landuse parameters. The climate was generated for 50 years with the WEPP model's own climate generator CLIGEN (Flanagan and Nearing, 1995). CLIGEN uses the statistics of various observed climate parameters for a particular station (here: Tombstone, Arizona). The soils and land cover parameters were taken from the WEPP soils and land cover data base (McNeal-AZ and Creosote and Whitethorn; Nearing, et al. 2005). The long-term Cs137 measurement sample points (Ritchie et al., 2005) were converted to a raster grid with a 1-meter cell size; each cell contained that value of erosion/deposition recorded from the field observations.





b) Channel segment CSA



c) Legend for d), e), and f)

a) Hillshade of 1-m DEM

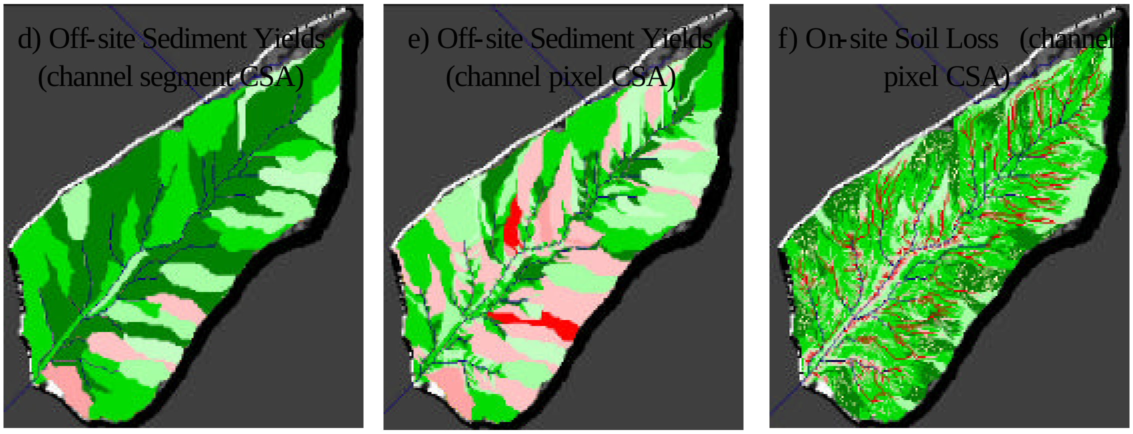


Figure 7. GeoWEPP input data sets and simulation results for different hillslope representations (CSA=Contributing Source Areas).

4. Preliminary Results and Discussion

A series of GeoWEPP simulation runs for each watershed representation and the three different DEM resolutions resulted in different pattern: off-site sediment yields from contributing source areas to channel segments (Figure 7d), off-site sediment yields from contributing areas to channel pixels (Figure 7e), and on-site soil loss along flowpaths to channel pixels (Figure 7f). Both, the off-site and the on-site assessment were mapped with a target value of 10 t ha^{-1} yr^{-1} (see legend Figure 7c). As one can see from the assessment results, we have various levels of detail and as a consequence of different hillslope representation different results. The results are within the expected range of observed long-term soil erosion and deposition, but its spatial pattern within the watershed is quite different.

While most of the Cs137-sample sites recorded soil erosion and only a few soil deposition, the simulation results were in agreement with our simulation results. The degree of agreement varied for the three hillslope representations and the cell size resolution. The cause of these discrepancies can be due to a number of factors. First, GeoWEPP only models converging flows, not diverging flows. A resulting divergence would result in a lower sediment carrying capacity resulting in deposition. DEM smoothing in the data preparation could also result in the lack on deposition. If a portion of the topography is smooth where there is normal a dip where pooling can occur, could lead to erosion conflicts. Finally, the resolution of the DEM must also be taken into account. There may be topographic issues occurring at a resolution smaller than 1m that may be the cause of the deposition. In general, one needs to take into account that the long-term erosion and deposition rates are a result of an ever-changing micro-topography. Since we do not have multi-temporal terrain models based on the same measurement technique we may have difficulties in representing the change of the topography over time. WEPP is a steady state model and does not take into account dynamic changes on the topography during a simulation.

We are currently statistically evaluating how well we represent the properties of hillslopes and the detail of processes in our model approach (more detailed and quantitative results will be presented at the meeting).

5. Conclusion

The experience of coordinating scaling theory, implementation procedure, and application indicate that Data Collectors, GIScientists, Modellers, and Decision Makers have to effectively communicate and understand the importance of aggregating and disaggregating information to validate and produce useful simulation results. The Water Erosion Prediction Project (WEPP) model is a representative hillslope and watershed model that requires the aggregation of spatial information before a process based model run. GeoWEPP allows the user to take advantage of various methods to represent the terrain as contributing areas to channel segments and pixels. However, it has to be determined, if we necessarily achieve better results in using either of the three model simulations.

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