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Spatial and Temporal Model Validation: Representing Landscape Properties and Processes across Scales

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Abstract: Continuous modeling of landscape processes and their validation requires representing environmental properties for model input and output across scales. A combination of a scaling theory, a Geospatial Project Management Tool (GeoProMT), and a GIS-based environmental modeling interface, allows interdisciplinary collaborators to efficiently handle and communicate the scaling (or transformation) of geospatial information of properties and processes across scales. This integrated approach of theory, project management tool, and modeling interface can be applied to any environmental model and software development. The integrated modeling is based on the Geospatial Interface for the Water Erosion Prediction Project (GeoWEPP) that enables soil and water conservationists to assess soil erosion taking into account detailed topographic, soils, and land use pattern to derive soil redistribution patterns at various spatial and temporal scales. Short-term, event-based and long-term, continuous validation studies in forest and rangeland have shown that the combination of different representations of hillslopes, the hillslope-channel interface, and the channels allows land managers to assess on- and off site impacts with the same underlying model at different spatial and temporal scales. Detailed climate, runoff and sediment time series were used to parameterize and validate the models performance. While event-based discharge and sediment measurements at silt fence studies and watershed outlets were used to validate short-term performance, long-term discharges and distributed ^{137}Cs samples on hillslopes were used to assess the long-term discharges and soil redistribution patterns over a 50-year time period. The results of this integrated model design and validation approach will guide modelers in other applications to a more effective and valid representation of landscape properties and processes.

Keywords: GIS; Scale, Soil Erosion, Modeling, Validation, Project Management

1. INTRODUCTION

Practical decision-making of environmental managers assessing the impact of natural variability and the impact of human activities often involves using environmental process models linked with Geographic Information Systems (GIS). Optimum use of these techniques for such decision-support requires careful and coordinated consideration of how the natural processes, the gathered observations, the modeling algorithms and related uncertainties are represented in data and simulation models used. To avoid wasting resources and time on inappropriate data collection, improper model use, and resulting poor decision-making, there is a pressing need for a scientific and functional framework within which to examine implementation and use of geo-spatial assessment tools. To be useful for researchers, engineers, and decision-makers, integrated environmental system simulation approaches must consider the spatial and temporal variability in natural processes and utilize as much as possible of all and the latest data sources that are available at variable scales.

There are certain limitations in the data formats used in Geographical Information Science (GIScience) and modeling tools to represent environmental properties and processes appropriately and accurately. With the latest methods in data gathering methods, we achieve an increasing amount of detail in representing environmental properties at a particular scale, but are still unable to communicate effectively among participating disciplines using this detailed information to predict landscape processes at various spatial and temporal scales.

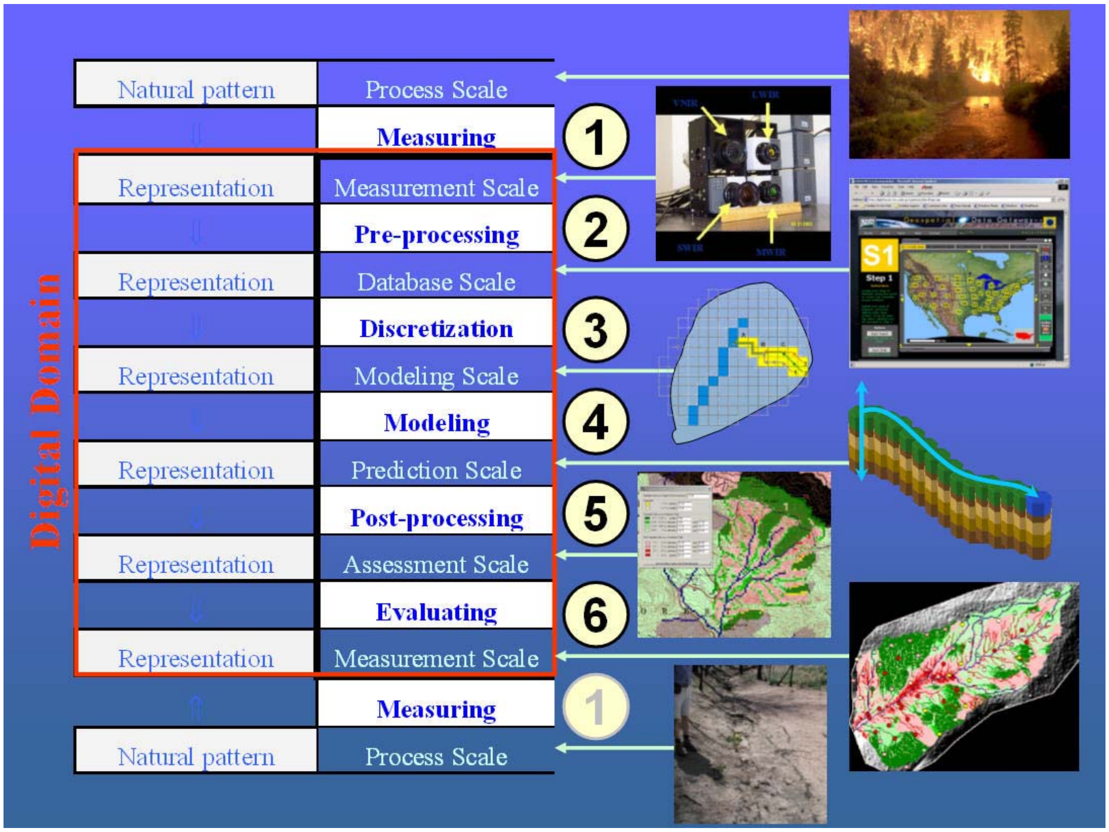


Figure 1. Scaling theory describing and documenting the transformation of information across scales.

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].

This paper describes the challenges of transforming information across scales and disciplinary boundaries offering an integrated assessment approach combining a scaling theory, a meta-data information management, and geo-spatial interface assisting model users and developers to design the next generation of integrated environmental models: models that are based on a holistic perspective environmental systems and information systems integrating monitoring and modeling.

2. THE SCALING THEORY

In using process models for decision-making the primary focus is basically on the decision-maker's scales of interest (assessment results), availability of data sets that might support appropriate model applications (assessment base), and the choice of a model that is adequate for the decision-making goals [see also Hoosbeek and Bryant, 1992] (assessment core). These three concurrent initial steps define the questions to be answered as well as the models and data sources to be used. In general, however, it is potential users' scales of interest, and scales of readily available data that should drive model design or selection, as opposed to using or designing the most sophisticated process model as the starting point and then determining data needs and result scales (Renschler, 2003).

Because integrated geo-spatial assessment requires careful consideration of all the steps in utilizing data, modeling and decision-making formats, each step in the scaling sequence must be assessed in terms of how data is being *scaled*. Scaling is here referred to as the transformation of information from one spatial/temporal scale to another (e.g. an interpolation, aggregation, disaggregation, etc.). Usually data transformation in the digital domain occurs in the following sequence (Figure 1): (1) Process Scale, (2) Measurement Scale, (3) Database Scale, (4) Modeling Scale, (5) Prediction Scale, (6) Assessment Scale, and again (1) Process/Validation Scale.

The two basic scaling steps at the *Process Scale* (Figure 1; Step 1) represent the transformation of a true pattern of a natural process to measured data, and all other steps deal with digital information handling. The main reason for assessing data transformation results at each step throughout the sequence by considering each to be simultaneously a *Validation Scale* is to ensure that the results of each step maintains those characteristics of the original data that are critical in controlling the final decision-making. For example, if aggregated data lead to results that vary enough from those produced using original data that it will affect the identified management decision, it is critical for a model developer to find out about it for recommendation purposes, a (geo-spatial algorithm) developer to report about it in an attached metadata file, and a user to get to know about it for instance during the data transformation (scaling) takes place.

Similarly, if the final management decision at the *Validation/Process Scale* is not sensitive to the use of readily available aggregated data, there is no need to spend time and resources on collecting more detailed data. Thus, an additional benefit is that this assessment allows identification of areas where less sophisticated approaches or less restrictive data requirements might be used without compromising the final outcome of the decision-making process. However, such an assessment might also identify steps where data inaccuracy or transformations introduce error or uncertainty that is beyond tolerable levels in terms of the impact on final decision making.

Explicit recognition of this helps reduce the risk of poor decision-making. It is important to recognize that the scaling steps can also be used as a framework for building a sequence of data transformations focused on providing results that are both adequate and accurate enough for the decision-maker's scales of interest. Enabling the user to set certain thresholds for acceptance along this sequence of data transformation creates awareness and a level of user confidence that the interface handles data and model in an appropriate way.

3. EFFECTIVE DATA MANAGEMENT

As a result of successful interdisciplinary, collaborative research, the Geo-spatial Project Management Tool (GeoProMT) was developed. GeoProMT is an internet-based interface for the management of shared geo-spatial and multi-temporal information such as measurements, remotely sensed images, and other GIS data (see also Figure 1). Integral to the GeoProMT framework is role-based access control (RBAC), where data access permissions and data users are associated with appropriate roles, enabling efficient collaboration among participants of large interdisciplinary geo-spatial projects. The mission of collaborative investigators was the development and integration of user-friendly GIScience and environmental modeling tools using readily available data sets to support a rapid, practical and effective decision-making in integrated environmental and disaster management [Renschler et al., 2006].

3.1 Observations at the Process Scale

Decision-making at a particular scale requires understanding natural variability and the limitations of observations at the process scale. GeoProMT requires all collaborators to investigate and document the challenges, techniques, and limitations of measuring environmental properties and processes as well as their spatial and temporal scales and natural variability.

3.2 Representation at Database Scale

Information technology provides a wide range of users with access to large and varied databases and sophisticated analysis tools, often with little information provided on data sources, measurement techniques and other data transformations. The collaborators are required to provide a detailed description of each data collection method and all data processing steps storing it as meta-data with GeoProMT.

3.3 Pre-processing of Model Input

Some model input parameters typically have to be derived from other data, although these data may already be stored at an appropriate database scale. Manipulation of these data sets such as to delineate a flow path and gradients in a landscape are additional scaling steps with their own inherent errors in the data processing algorithms. Project collaborators are again required to investigate and document this in meta-data.

3.4 Processes at the Model Scale

Scaling is inherent in any environmental process model used in an assessment approach. The representation of processes through models is done with the intent of predicting patterns and variances of environmental properties at certain scales of interest, to support the decision-making process. The collaborators need to investigate and describe any process representation in models and the data transformation that takes place in this step.

3.5 Post-processing at the Assessment Scale

Post-processing is necessary when model results are not at the scale of interest for the decision maker. Post-processing is a manipulation of the results, such as averaging, interpolating, and mapping, with all the potential implications associated. Recognition and understanding of this type of sensitivity of post-processed model output (on which decisions might be made) to data scaling is important as it helps guide sensible decision-making based on the produced assessment results.

3.6 Validation at the Measurement Scale

The final scaling step in this integrated environmental assessment, and a step often neglected, relates to comparison and evaluation of the model output with observed and quantified natural patterns. The evaluation of model output is essentially a scaling step with comparison against measurement data gathered at the process scale (step 1 above). The collaborators have to go through the entire data management cycle to understand the implications of data processing in an interdisciplinary, integrated environmental assessment with GIS and environmental models. GeoProMT can be used as digital data repository in developing or using any information processing step in a project such as a data algorithm or any geospatial model in this regard.

4. GEOSPATIAL MODEL INTERFACE

Traditional process models, such as the Water Erosion Prediction Project (WEPP) [Flanagan and Nearing, 1995], were not typically developed with a flexible Graphical User Interface (GUI) for applications across a wide range of spatial and temporal scales, utilizing readily available geo-spatial data of highly variable precision and accuracy, and communicating with a diverse spectrum of users with different levels of expertise. As the development of the Geo-spatial interface for WEPP (GeoWEPP) [Renschler, 2003] demonstrates, that also the GUI plays a key role in facilitating effective communication between the tool developer and user about data and model scales. The GeoWEPP approach [Renschler, 2003] illustrates, that it is critical to develop a scientific and functional framework for the design, implementation and use of such geo-spatial model assessment tools. The way GeoWEPP was developed and implemented using the previously described scaling theory leading to a practical approach for designing geo-spatial interfaces for process models. GeoWEPP accounts for fundamental water erosion processes, model and users needs, but most important it also matches realistic data availability and environmental settings by enabling even non-GIS-literate users to quickly assemble the available geo-spatial data to start soil and water conservation planning. In general, it is potential users' spatial and temporal scales of interest, and scales of readily available data that should drive model design or selection, as opposed to using or designing the most sophisticated process model as the starting point and then determining data needs and result scales.

The following case studies illustrate how helpful the integrated approaches of the scaling theory, GeoProMT and GeoWEPP are to manage data effectively and validate process models in realistic data settings and understand the limitations of the currently available data, model technology, and information provide to support decision-making processes.

5. MODEL VALIDATION

5.1 Short-term erosive events

Over the past decade the continuous process-based WEPP model provided Burned Area Emergency Rehabilitation (BAER) Teams with a hillslope modeling tool to mitigate hillslopes of wild fire areas [Elliot, 2004]. Since about five years, a series of over 10 GeoWEPP workshops at professional meetings enabled the author to systematically collect information about the users' spatial and temporal scales of interest, the availability and needs for model input data, and the capabilities of models to produce useful information needed to support decision-making. GeoWEPP was confirmed to be the choice of the users since it requires a minimum of model calibration to simulate ungauged watersheds (in fact it is more a validation than calibration procedure) and uses readily available data sets from public sources.

The GeoWEPP performance (without any calibration!) was tested with data series collected at clean out dates of six paired silt fences at two locations and a small watershed data in the burned Bitterroot National Forest, Montana (Renschler et al., 2005). There were three weather stations to record detailed precipitation at all three sites even though they were all located within a 1-km^2 area. Four stands of mixed ponderosa pine and Douglas fir were chosen to evaluate the variability of post-fire erosion rates on steep slopes (greater than 40 percent) after high severity wildfires in the Bitterroot National Forest of west-central Montana after the 2000 fire season.

Table 1: Observed and predicted event-based precipitation, average total runoff, and average total sediment yields at six 0.01-ha silt-fences at L1 and H1 sites each, and at one 4.2-ha watershed W1, Bitterroot National Forest, Montana.

Date	0.01-ha L1	0.01-ha H1	4.2 ha-W1
Observed precipitation at each site (mm)			
7/15/01	*4.8*	*5.6*	*4.1*
7/20/01	*14.7*	*9.4*	*9.7*
7/21/01	*11.2*	*12.2*	*9.7*
*7/22/01**	*Σ=34.0*	*Σ=46.7*	*Σ=27.2*
7/30/01	*21.6*	*21.2*	*21.3*
*8/11/01**	*Σ=21.6*	*Σ=21.2*	*Σ=21.3*
Simulated Runoff for 3.7 ha watershed (mm)			
7/15/01	**0**	**0**	**0**
7/20/01	**3.88**	**0.39**	**0.03**
7/21/01	**1.23**	**1.23**	**0**
*7/22/01**	*n.a.*	*n.a.*	*Σ=0.03*
7/30/01	**0**	**0**	**0**
*8/11/01**	*n.a.*	*n.a.*	*Σ=0*
Sim. Sediment Yields for 3.7-ha watershed (t ha^{-1})			
7/15/01	**0**	**0**	**0**
7/20/01	**4.69**	**0.41**	**0.525**
7/21/01	**0.59**	**1.20**	**0**
*7/22/01**	*Σ=48.543*	*Σ=0.162*	*Σ=0.475*
7/30/01	**0**	**0**	**0**
*8/11/01**	*Σ=0.070*	*Σ=0.018*	*Σ=0*

**clean out dates with observed total sum since last clean out; n.a. = runoff at silt fences not available.*

The objectives were a) to identify the spatial and temporal trends of post-fire erosion; and b) to identify and quantify site and environmental factors affecting post-fire hillslope erosion. Rainfall intensity and not necessarily the total rainfall amounts during a precipitation event was the most significant factor for explaining post-fire erosion rate variability (Table 1).

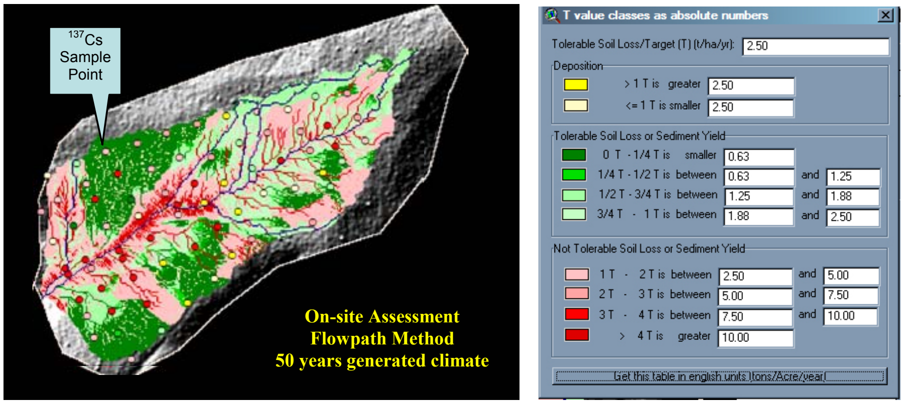
The observations show that the short-duration, high intensity thunderstorms of July 15th, 20th and 21st caused erosion rates at the silt fence sites ranging from 0.162 to 48.543 t ha^{-1} (table 1). Instead the much larger, long duration, low intensity rains on July 30th produced very little erosion (< 0.01 t ha^{-1}). GeoWEPP was able to predict accurately runoff (observed: 0.03 mm; simulated: 0.03 mm) and total sediment yield (observed: 0.475 t ha^{-1}; simulated: 0 .525 t ha^{-1}) for the 4.2-ha observed watershed and GeoWEPP-delineated, simulated 3.7-ha watershed.

The observations and simulations for the silt fence data indicate (even when simulating a 0.01-watershed; not shown here), that the spatial and temporal variability of model input parameters is very difficult to represent in the model input as well as the model simulation (note the three orders of magnitude difference of simulated runoff and the one order of magnitude difference of simulated sediment yields at the watershed scale on July 20th). Despite the differences at the silt fence scale, the GeoWEPP watershed simulations at the 4.2-watershed scale appears to represent the integrated signal of runoff and sediment yield at the watershed outlet. So, how can one validate what happens at these smaller scales within a watershed? In another project an investigation is under way to compare long-term soil redistribution patterns in landscapes.

5.2 Long-term soil erosion pattern

Understanding erosion processes and carbon sequestration patterns are keys to developing methods to determine sediment and carbon budgets at the landscape scale. Methods to simulate and assess the dynamics of erosion and carbon sequestration processes with spatially-distributed erosion models allow developing appropriate land use Best Management Practices (BMPs) and policy recommendation [Renschler and Lee, 2005]. GeoWEPP enables taking advantage of detailed topographic pattern to derive soil redistribution patterns at various scales: watershed with representative hillslopes or along flowpaths within landscapes. The latter method allows taking full advantage of the spatial resolution of detailed topographic, land cover and soil maps to derive soil loss and sedimentation pattern in landscapes (Figure 3; Figure 1; step 6).

In the case of the nested Lucky Hills watersheds – a rangeland ecosystem study site near Tombstone, Arizona – detailed climate, runoff and sediment time series were used to parameterize and validate the performance of a spatially distributed soil erosion model. The distributed ^{137}Cesium samples were used to validate the long-term spatial redistribution of sediments [Ritchie et al, 2005]. Overtime, fluvial processes remove ^{137}Cs-bounded soil particles from the upper hillslopes to lower hillslope parts within a watershed. By measuring the amount of ^{137}Cs-bounded material at a site, the amount of erosion and deposit over time can be calculated. These measurements were then used to validate the erosion model simulation results on long-term soil redistribution pattern within the watershed as well as the event-based runoff and sediment yield measurements at the outlets of the nested watershed. Even though the model results for the watershed outlet fit the observed data series, ongoing research indicates that there is a complex link between the scales of sample distribution, model input parameter, watershed delineation, model algorithm, and model output post-processing.



Tolerable Soil Loss/Target (T) (t/ha/yr): 2.50

Deposition

🟨	> 1 T is greater	2.50		
🟨	<= 1 T is smaller	2.50		

Tolerable Soil Loss or Sediment Yield

🟩	0 T - 1/4 T is smaller	0.63		
🟩	1/4 T - 1/2 T is between	0.63	and	1.25
🟩	1/2 T - 3/4 T is between	1.25	and	1.88
🟩	3/4 T - 1 T is between	1.88	and	2.50

Not Tolerable Soil Loss or Sediment Yield

🟥	1 T - 2 T is between	2.50	and	5.00
🟥	2 T - 3 T is between	5.00	and	7.50
🟥	3 T - 4 T is between	7.50	and	10.00
🟥	> 4 T is greater	10.00		

Figure 2. Soil loss in tolerable (dark and light green), non-tolerable levels (light and dark red), and deposition (yellow) compared to soil redistribution sample sites in the nested Lucky Hills Watersheds, AZ.

6. CONCLUSIONS

The integrated assessment of the spatial and temporal variability of natural properties and processes combining a scaling theory, geo-spatial project management, and process modeling allows collaborators to communicate effectively across disciplinary boundaries. The successful implementation of GeoWEPP for BAER team assessment of post-fire soil erosion in burned watersheds shows the usefulness of the proposed integrated approach. However, the analysis of the erosion and deposition simulation results is still a challenge due to the fact that there is a very interesting, but extremely complex relationship between the spatial and temporal observations, model inputs discretization, and the model outputs.

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