SMALL WATERSHED MODELING WITH WEPP USING GRID-BASED DEMS AND GIS

by

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Summary:

Two methods for automatically applying the Water Erosion Prediction Project (WEPP) model with digital elevation models (DEMs) and geographic information systems (GIS) are presented and evaluated using 6 research watersheds in 3 different locations in the U.S.A. The methods perform as well as a manual application of WEPP to the watersheds by an expert user. The effects of using DEMs of different resolutions are also presented and discussed.

Keywords:
Watershed modeling, WEPP, GIS, DEM

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ABSTRACT

Two different methods utilizing geographical information systems (GIS) and digital elevation models (DEMs) are described and evaluated for applying the Water Erosion Prediction Project (WEPP) model to assess water erosion and runoff in small watersheds. The first approach, called the Hillslope method, presents an automated method for the application of WEPP through the extraction of hillslopes and channels from DEMs. The second approach, called the Flowpath method, uses WEPP model simulations on all possible flowpaths within a watershed. The two methods were applied to five field size (0.59 to 2.7 ha) research watersheds, two from Watkinsville, Georgia, three from Holly Springs, Mississippi, and one small watershed (29 ha) in Treynor, Iowa. Both methods were evaluated for assessing watershed erosion using different DEM grid resolutions. Simulations were conducted using 1, 3, 5, and 10-meter resolution DEMs for the field sized watersheds and 5, 10, 15, and 20-meter resolutions for the Treynor watershed. Statistical analysis for all methods and watersheds, were performed by comparing predicted vs. measured runoff and sediment yield from the watershed outlets for runoff and sediment loss. A comparison of erosion from only hillslopes for all three methods indicates that the Flowpath method is statistically comparable to the other methods. Comparisons of both simulation methods to a manual application of WEPP by an expert user for all watersheds were also conducted at each DEM resolution level. The results indicate that the automatic Hillslope method performs as well as a manual application of WEPP by an expert user for all watersheds.

INTRODUCTION

Soil erosion by water is a cause of non-point source pollution in watersheds that can lead to loss of fertility and can have an adverse effect on water quality and the ecosystem. Erosion models, such as the Water Erosion Prediction Project model (WEPP), can be useful tools for estimating erosion and runoff from watersheds (Flanagan and Nearing, 1995). An interface between the WEPP model and a GIS can help reduce the time and cost of predicting erosion and runoff from watersheds where GIS data is readily available.

Currently, a user applying the WEPP watershed model has to use topographical paper maps to manually delineate the watershed of interest, the channel network in the watershed, individual hillslopes, and a representative slope profile for each hillslope. Crops, soils, and management practices also have to be defined for each hillslope. Each hillslope is then represented as a rectangular area with a single slope profile that drains into a channel as shown in Figure 1. WEPP has the ability to further simulate the division of a hillslope's slope profile into overland flow elements. This feature is used when simulating watersheds or hillslopes containing more than one soil type or crop/management per hillslope. However, this feature was not used for the studies presented here, since each hillslope within the watersheds had a uniform soils and crop/management practices.
The process of discretization is time consuming for the user and can be a subject of discrepancy and variability between users. Two methods to interface WEPP and a GIS have been created to facilitate the discretization process. These methods use the TOPographic evaluation, drainage identification, watershed segmentation and subcatchment parameterization (TOPAZ) automated digital landscape analysis tool (Garbrecht and Martz, 1997) algorithms to identify the watershed, channels, and hillslopes. Additionally newly developed algorithms were used to identify the representative slope profiles from digital elevation models (DEM).

BACKGROUND

The use of geographic information systems (GIS) by individuals, government agencies, and private consultancy agencies to manage and analyze spatial data such as digital elevation models (DEM), soils maps, landuse maps, and other maps is increasing dramatically. This in turn is creating an ever growing demand for developers and researchers to create new algorithms for environmental modeling.

With the growth of GIS, a variety of new environmental modeling applications and algorithms to extract hydrologic parameters have been created. Moore et al. (1991) describes many of the current algorithms and future applications. Of particular interest are algorithms that provide flow routing within watersheds and methods to smooth data and calculate slope values. Desmet and Govers (1996) also provide a good review of the current algorithms dealing with flow routing on a cell by cell basis. These algorithms have been used to integrate erosion and runoff models such as USLE, SWAT, AGNPS, ANSWERS, and others. WEPP has also been used together with a raster based GIS (Savabi et al. 1995). In this study, the GRASS (CERL, 1993) GIS was used to obtain some of the physical parameters required by WEPP for the Purdue University animal science watershed, but the issues regarding hillslope, channel, and representative slope profile creation based on DEMs were not addressed.

MATERIALS AND METHODS

Two methods developed to apply WEPP using DEMs and GIS are called the Hillslope and Flowpath methods. These methods were evaluated using observed data from ARS experimental watersheds at Treynor, Iowa, Holly Springs, Mississippi, and Watkinsville, Georgia.

Research watersheds and DEMs

The automated methods of applying WEPP to watersheds were tested using six research watersheds, the largest one being in Treynor, Iowa, measuring 29 ha and having 6 years of available daily measured data. The other five watersheds, three in Holly Springs, Mississippi and two in Watkinsville, Georgia, have areas between 0.59 and 2.7 ha and have 3 to 8 years of measured daily data. Additional information about soils and crop/management practices for these watersheds is presented in Table 1.

The most important data layer for discretizing the watershed components is the elevation map. Topographic information for the Treynor watershed was obtained by aerial surveys with ground control. Even though a smaller resolution could be used, the quality of the data and the size of the watershed suggested that a 5 meter grid was the most appropriate for this study. This original
DEM was then degraded to resolutions of 10, 15, and 20 meters to study the effects of DEM resolution on prediction results. Elevation data for the Holly Springs and Watkinsville watersheds were obtained from contour-based field surveyed maps. These were digitized and a grid based DEM was created for each watershed. DEM resolutions of 1, 3, 5, and 10 meters were then created and used for this study.

Hillslope method
The Hillslope method consists of automatically defining the watershed components (hillslopes and channels). Hillslopes and representative slope profiles were extracted by using a DEM of the watershed and algorithms that simulate the flow of water between cells in the DEM. The coding for the hillslope and profile creation algorithms was done in the FORTRAN programming language and the TOPAZ program was used for the extraction of routing features in the watershed. Even though GIS programs such as Arc View have add-on programs such as Spatial Analyst™ that can handle grid based flow routing, TOPAZ was chosen for its ability to overcome limitations of previous algorithms with respect to drainage identification in depressions and over flat surfaces (Garbrecht et al., 1996).

Channel location and lengths are initially defined by selecting a critical source area (CSA). The CSA represents a drainage area whose concentrated water flow defines the beginning of a channel (Garbrecht and Martz, 1997). When using a DEM, the CSA represents a certain number of cells flowing into one single cell (defined as the starting point of a channel). Correct identification of channels may be verified by aerial photography or field surveys. CSA values for the Watkinsville watersheds were 0.5 hectares (ha), for the Holly Spring’s watershed WC1 it was also 0.5 ha, but for watersheds WC2 and WC3 it was 0.25 ha. The CSA value for the Treynor watershed was 4 ha. However, the exact point of channel initiation can be influenced by other factors such as ground slope, soil, management, and climatic factors (Montgomery and Dietrich, 1989; Martz and Garbrecht, 1992). Other WEPP channel input parameters such as actual width, shape, depth, and erodibility have to be provided by the user.

Hillslopes are defined to drain to the left, right, and top of the channels created from the DEM (Figure 1). A representative slope profile is obtained by a weighted average of all possible flowpaths in the hillslopes. Flowpaths are defined as the route water travels flowing from one cell to the next, starting from a cell where no other cells flow into it and ending at the point where a channel is reached. Within each hillslope there may be a large number of flowpaths, some which start at the edge of the watershed or others at points inside the hillslope. Many flowpaths may eventually intersect as they reach the channel. Individual flowpaths were extracted by analyzing output files of the TOPAZ program. A representative slope profile for each hillslope was computed from all the individual flowpaths within the hillslope through weighting flowpaths by their area and length, and comparing each cell length of a flowpath to all other matching cell lengths from flowpaths starting from the channel and moving up-slope. It was assumed that the flowpaths with greater area and longer lengths contributed proportionally more than the smaller and shorter flowpaths to the representative profile. Since cells are square, cells flowing in a diagonal fashion have a longer length than a flowpath with an equal number of cells but with cells flowing horizontally or vertically into each other, hence the reason to consider both area (number of cells) and length. The following equation illustrates the computation of a representative slope profile for a hillslope:
\[ E_i = \frac{\sum_{p=1}^{m} z_{pi} \cdot k_p}{\sum_{p=1}^{m} k_p} \quad [1] \]

Where \( E_i \) is the weighted slope value for all flowpaths at a distance \( i \) from the channel; \( z_{pi} \) is the slope of flowpath \( p \) at a distance \( i \) from channel; and \( k_p \) is a weighting factor for flowpath \( p \). The weighting was done by multiplying the upstream drainage area (\( a_i \), area of cells in the flowpath) times flowpath length (\( k_i = a_i \cdot l_i \)). Since this equation calculates a profile with a length equal to the longest flowpath, it is also necessary to determine the appropriate length of the profile. For hillslopes draining laterally into channels, the width of the hillslope is set equal to the length of the channel. The length of the hillslope is then calculated by dividing the total hillslope area by the width. The representative profile is then truncated so that it is equal to the calculated length starting at the bottom of the hillslope. For hillslopes that drain into the top of the channel, the length was determined by a similar method of weighting all flowpaths illustrated by the following equation presented in Garbrecht et al. (1996):

\[ L = \frac{\sum_{p=1}^{n} l_p \cdot a_p}{\sum_{p=1}^{n} a_p} \quad [2] \]

Where \( L \) is the hillslope length, \( l_p \) is the flowpath length, \( a_p \) is the area represented by the cells in the flowpath, and \( n \) is the number of flowpaths in the hillslope. The width of the representative hillslope profile is then easily calculated by dividing the total hillslope area by this length. The two main assumptions for this case are that the flowpaths are the routes traveled by water and that larger and longer flowpaths contribute more than smaller and shorter flowpaths (Garbrecht et al., 1996).

**Flowpath method**

The second method of applying WEPP to a watershed using GIS and DEMs is the Flowpath method. In this procedure WEPP is applied to all possible flowpaths in the watershed. The problem of interaction between flowpaths is handled in a unique way. All points where flowpaths drain into a channel are identified. An average sediment and runoff discharging into the channel for every one of these points is then calculated by averaging the independent application of WEPP to each flowpath draining to the particular point. The width used for the WEPP application of the individual flowpaths is calculated by dividing the total area of all flowpaths draining to that particular point by the length of the individual flowpath.

The maximum number of points of discharge to the channels is the number of cells that make up the channel multiplied by 2 (left and right sides). For each of these points a channel segment could be defined to route the water to the outlet of the channel. However, since this would be done on a cell by cell basis down the channel, the current channel logic used in WEPP may not be dimensioned large enough to correctly handle this situation. Another alternative would be to add the contribution for all points draining laterally in the channel. This alternative would require modification of the current WEPP code to handle channel routing with unevenly distributed lateral flow to the channel. Since it was not the intention of the authors to change the
WEPP code, these modifications were not further pursued. This implies that a comparison of the Flowpath method to observed soil loss results from the watershed outlets would only be appropriate if there was no scouring or deposition occurring in the channels. However, erosion from hillslopes can be compared between all methods.

**Experimental setup**

A manual application of WEPP to all research watersheds was conducted to ensure a basis of comparison for the automatic methods. This manual application represented an expert WEPP user's ideal simulation. For the Treynor watershed, WEPP was applied using a similar discretization level as done by Kramer (1993). However, the application was improved using better channel parameter descriptions and default soils data from the WEPP soils database. The manual applications to the Holly Springs and Watkinsville watersheds were done using data from a previous validation of WEPP for these watersheds by Liu et al. (1997).

Comparisons of the methods to actual watershed outlet runoff and sediment loss were done on an event by event basis and cumulative total results. A direct comparison between the Hillslope and manual applications and the measured watershed outlet results was possible because channels were simulated in both of these applications of WEPP. Since the Flowpath method does not simulate channel erosion, hillslope erosion comparisons (excluding channels) were more appropriate. These were used to compare differences between DEM resolutions and to evaluate the performance of the Flowpath method.

**RESULTS and DISCUSSION**

For the six watersheds studied, comparisons of total simulated vs. measured results indicated that WEPP performs satisfactorily in simulating sediment yield and runoff for all watersheds. In general, runoff results were similar to measured results on both an event-by-event basis and for total runoff over time. Normalized simulated sediment yield totals from the watershed outlet are plotted against measured values for the Hillslope method and the manual application in Figure 2. The regression lines indicate a good fit and a low variance for both methods. The slope and intercept of the regression fit show that the Hillslope method performs as well as the manual application of WEPP.

Actual values for the total simulation results are shown in Table 2 for the manual application, the Hillslope method, and the Flowpath method. These results also show the differences between hillslope erosion and channel erosion. The columns labeled hillslopes show predicted results for hillslope sediment delivery and the columns labeled channels show results from the outlet of the watershed. Differences between these are caused by either the channels acting as sediment traps or being in an eroding mode. As mentioned before, the manual application and the Hillslope method can simulate channel erosion, however, the Flowpath method can not do this at the present moment. For most of the watersheds and especially for the Holly Springs watersheds, the channel has a great influence on the prediction of sediment yield from the outlet. However, a statistical test on the results of all watersheds combined revealed that there was no significant difference between the predictions of only hillslope erosion between the manual application and the two automatic simulation methods (Table 2).
The effects of DEM resolution on the results of the simulations using both the Hillslope and Flowpath method were studied and results for total sediment yield for the hillslopes within the watersheds are presented in Figure 3. Additionally, dashed lines in Figure 3 represent results from the manual application of WEPP to these watersheds. In general both automatic methods produce similar results that in turn are similar to the manual application. For the Flowpath method, there is a slight increase in sediment yield results as the resolution is increased. This is observable in all watersheds, but it is most noticeable in the Watkinsville P2 watershed.

For the Hillslope method, most DEM resolutions studied predict similar sediment yield results. One exception is watershed P2 where there is a significant difference between the 1 meter resolution and the 3 and 5 meter resolutions. A closer look at the calculated slope profiles for each hillslope in this watershed provide some clues to the differences in their results. This is shown in Figure 4 where soil loss down the profile is plotted for each hillslope. There is a great variation in soil loss down the profile for the 1 meter resolution. Sediment loss for this resolution changes from a detachment regime to a depositional mode frequently as it approaches the end of the hillslope. This can be attributed to rapid changes in slope over short distances caused by either actual topographic features or DEM errors due to the very fine grid resolution. As the resolution becomes coarser, the soil loss is more uniform. This can also explain the slight increase in sediment yield predictions of the Flowpath method as resolution becomes coarser. As the watershed hillslopes become smoother, the Flowpath method using WEPP predicts less depositional areas and the overall sediment yield is increased.

The results of this study lead to the observation of four significant influences of DEM grid resolution on modeling with WEPP. The first one is that the watershed delineation is less accurate with lower resolution data. The outline of the watershed becomes blocky and will eventually lose its original shape when the resolution is too coarse. This can be seen in Figure 4 for the Watkinsville P2 watershed. The second observation is similar to the first. Channel networks and hillslopes become more difficult to define as resolution is reduced. The third significant observation when degrading the resolution of DEMs is that the average slope of the hillslope profiles decreases. Soil loss either increase or decrease depending on whether the change in slope is due to removal of DEM errors that can cause areas of deposition or an overall decrease in slope. The fourth observation of using different DEM resolutions is that hillslope profiles become smoother as resolution is decreased leading to a more uniform sediment loss down the profile. Again, this can be observed in Figure 4 for each of the hillslopes of Watkinsville P2 watershed when the resolution becomes coarser.

SUMMARY and CONCLUSIONS

Two methods for automatically applying WEPP using DEMs and GIS were presented and evaluated with six research watersheds in three distinct geographical regions using four different DEM resolutions. The first method, called the Hillslope method, works by using a DEM to discretize the watershed into channels and hillslopes with their representative slope profiles. WEPP was then applied to the entire watershed including channels. The second method, called the Flowpath method, works by applying WEPP to each individual flowpath within the watershed. This method, however, is only used for hillslope erosion prediction because channels were not simulated. Both methods were applied using four DEM resolutions and compared to a
manual application by an expert WEPP user. The Hillslope method was also compared to actual runoff and sediment yield from the watershed outlet.

In general, the automatic methods work as well as the manual application of WEPP by an expert user when predicting hillslope erosion. The Hillslope method was also comparable to actual sediment yield from the watershed outlet. The automatic methods gave consistent results for most of the DEM resolutions tested. However, the effects of the DEM resolution could be seen for some of the watersheds. As the grid cell size of the DEMs is increased the slope profiles of each watershed and flowpath become smoother which leads to a more uniform soil loss down the slope profile. As the resolution becomes coarser, the watershed boundaries and channel networks become more difficult to define. A basic rule of thumb for selecting the appropriate DEM resolution for modeling with both of these automatic methods can therefore be established as follows. If the results of soil loss down the profile seem to be erratic or bouncing up and down from erosion to deposition modes then the resolution used is probably too fine. On the other hand, if the watershed channel network or boundary is compromised, then the resolution is too coarse. Ranges of DEM resolution in between seem to provide similar results. It is also important to note that the prediction results as compared to the measured observations are dependent on the original survey accuracy of the DEM.

REFERENCES


Table 1. Research Watersheds

<table>
<thead>
<tr>
<th>Watershed (location)</th>
<th>Years of simulation</th>
<th>Area (ha)</th>
<th>Soils</th>
<th>Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2 (Treynor, Ia.)</td>
<td>1985-90</td>
<td>29</td>
<td>Monona-Ida-Napier series (Silt loam)</td>
<td>Corn</td>
</tr>
<tr>
<td>P1 (Watkinsville, Ga.)</td>
<td>1972-74</td>
<td>2.70</td>
<td>Cecil (Sandy loam and SCL)</td>
<td>Wheat, sorghum, barley, soybean, clover</td>
</tr>
<tr>
<td>P2 (Watkinsville, Ga.)</td>
<td>1973-75</td>
<td>1.29</td>
<td>Cecil (Sandy loam and SCL)</td>
<td>Corn, bermuda grass</td>
</tr>
<tr>
<td>WC1 (Holly Springs, Miss.)</td>
<td>1970-77</td>
<td>1.57</td>
<td>Grenada (Silt loam)</td>
<td>Soybean, meadow</td>
</tr>
<tr>
<td>WC2 (Holly Springs, Miss.)</td>
<td>1970-77</td>
<td>0.59</td>
<td>Grenada (Silt loam)</td>
<td>Corn, wheat, soybean</td>
</tr>
<tr>
<td>WC3 (Holly Springs, Miss.)</td>
<td>1970-77</td>
<td>0.65</td>
<td>Grenada (Silt loam)</td>
<td>Corn, wheat, soybean</td>
</tr>
</tbody>
</table>

Table 2. Total WEPP predicted erosion from hillslopes and channels (kg).*

<table>
<thead>
<tr>
<th>Watershed Name</th>
<th>Manual method</th>
<th>Hillslope method</th>
<th>Flowpath method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hillslopes</td>
<td>channels</td>
<td>% channel deposition</td>
</tr>
<tr>
<td>P1</td>
<td>160900</td>
<td>156300</td>
<td>3</td>
</tr>
<tr>
<td>P2</td>
<td>37300</td>
<td>30600</td>
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<td>300600</td>
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<tr>
<td>WC2</td>
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<tr>
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<td>111000</td>
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<tr>
<td>W2</td>
<td>2173100</td>
<td>1738800</td>
<td>25</td>
</tr>
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</table>

* Means of hillslopes for the three methods were tested using student t-test, Duncan's, and Tukey's comparisons of means, all of which gave the same decision results for hypothesis testing at \( \alpha = 0.05 \). The means were not statistically different at the 95% confidence level.
Figure 1. WEPP watershed modeling discretization.

Figure 2. Total sediment loss from each watershed (normalized by watershed area and number of events).
Figure 3. Hillslope sediment yields for Hillslope and Flowpath methods under different DEM resolutions.
Watkinsville watershed P2

a) Top hillslope soil loss with distance

Watershed boundary delineation

1m resolution 3m resolution

5m resolution 10m resolution

b) Left hillslope soil loss with distance

c) Right hillslope soil loss with distance

Figure 4. Hillslope method predicted soil loss down the slope profile of each hillslope of Watkinsville P2 watershed.