This is not a peer-reviewed article.
Pp. 428-433 in Total Maximum Daily Load (TMDL) Environmental Regulations–II
Proceedings of the 8-12 November 2003 Conference (Albuquerque, New Mexico USA),
Publication Date 8 November 2003.
ASAE Publication Number 701P1503, ed. A. Saleh.

EVALUATION OF GRID-BASED DISTRIBUTED SEDIMENT DELIVERY RATIO MODELS

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ABSTRACT

The emphasis on a watershed-scale approach to management of water quantity and quality has renewed the focus on hydrologic/water quality modeling at that scale. While the most widely used modeling approach to TMDLs continue to be a lumped approach using HSPF, there is also ongoing development of models that use a distributed parameter approach. In addition to the more traditional language-based simulation models, we are also seeing the development of some new modeling approaches that provide a spatially dynamic model built within a geographic information system (GIS) using the native GIS functions. The emphasis to date has been on predicting hydrologic responses, but approaches for modeling water quality constituents have also been developed.

In this preliminary study, three spatially distributed sediment delivery ratio methods (SDR) were evaluated in terms of spatial distribution of the delivery ratio. The three methods use 30m DEM as the base data set and provide a SDR value for each cell in the watershed. Two methods are based on flow velocity as a key model component, and third method is based on a weighted index of key factors. Results from two methods show a higher sensitivity to the flow network (upslope area) and the third method is more sensitive to land use patterns. In future work, those three methods as well as other spatially distributed method of estimating sediment yield with be

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compared with observed sediment yield data as well as with predictions of spatially distributed, widely used nonpoint source pollution (NPS) models.

KEYWORDS. Spatial distribution, SDR, GIS, sediment yield

INTRODUCTION

One of the major limitations in using HSPF effectively as a tool for TMDL development and for TMDL implementation planning is the spatial aggregation inherent in the model. This spatial lumping means that site-specific information is lost. The site-specific assessment is especially important as the EPA and the States move to include implementation as part of the TMDL development since implementation, by nature, requires site-specific assessment of pollutants.

One of the most important components in any NPS model is the erosion/sediment yield component since sediments can carry many other pollutants (e.g. phosphorus, pesticides). Since erosion processes include detachment, transport, and deposition, it is our position that a distributed parameter approach will best represent those processes due to the need to account for the along-the-flow-path interactions of those processes. Currently, there are methods that exist that treat erosion as a spatially distributed process and that utilize simple but representative concepts of the processes. The methods included in this preliminary evaluation are a method proposed by Jain and Kothyari (2001) (J-K), the SEDMOD approach (Fraser, 1999) that estimates the sediment yield in terms of sediment delivery ratio (SDR), and a cumulative time ratio (CTR) method. Jain and Kothyari's method estimates the sediment deliver ratio for each grid cell as a function of the cumulative travel time of flow to the watershed outlet or a point downstream of that cell. The SEDMOD approach is based on estimating a composite grid of SDR representing all cells in a watershed by combining the effects of six factors that control the potential for sediment delivery from each cell to any point downstream of that corresponding cell. The CTR method is described below.

METHODS TO BE EVALUATED

A preliminary study was conducted to investigate the general behaviour of thee different methods by visually comparing the sediment yield potential for cells representing the Stroubles Creek watershed in Virginia which has an area of about 3,000 ha. The methods included a duplication of Jain and Kothyari's method (Jain and Kothyari, 2001), the method adopted in SEDMOD (Fraser, 1999), and the cumulative time ratio (CTR). Following is a description of those methods.

Cumulative time ratio (CTR)

The CTR method, the SDR is proposed to be a function of flow velocity expressed as travel time. A reference travel time is based on the minimum value of Manning's n in the watershed. The SDR for each cell is a function of the ratio of reference travel time to "actual" travel time obtained using a Manning's n value appropriate for the actual land cover as shown in equation 1.

$$SDR_i = \frac{\sum_{i=1}^{m} \frac{l_i}{\frac{1}{n_{uniform}} S_i^{0.5} D_i^{0.67}}}{\sum_{i=1}^{m} \frac{l_i}{\frac{1}{n_i} S_i^{0.5} D_i^{0.67}}} \qquad (1)$$

where l_i is the local flow length in each cell, S_i is local slope, D_i is local flow depth, n_i is the actual Manning's n for the ith cell and $n_{uniform}$ is a minimum value of Manning's n that is taken to be the lowest actual observed value in the watershed, m is the number of cells along the flow path. The form of Manning's equation used was suggested by Ree (Ree et al., 1977). The rational behind this method of estimating SDR is that the amount of sediment reaching streams is a function of travel time to streams and that the amount may be represented by the ratio between travel times assuming all the watershed was paved (minimum flow resistance) versus travel times based the actual land cover.

Jain-Kothyari method (J-K)

Jain and Kothyari (2000) used a very similar procedure where gross erosion was estimated using the USLE. The authors selected a threshold for channel initiation that resulted in the total estimated stream length similar to that obtained from 1:25000 scale topographic maps. The method of estimating the SDR was based on the assumption that the SDR in a cell is a strong function of the travel time of overland flow within the cell which in turn is dependent on topographic and land cover conditions of the cell. They assumed the following empirical relationship

$$D_{R_i} = e^{-\gamma t_i} \qquad (2)$$

where t_i is the overland flow travel time from the *i*th cell to the nearest channel cell and γ is a constant coefficient for the catchment. The authors used a simple equation to estimate the flow velocity which was proposed by the US Soil Conservation Service (SCS, 1975) and is given by:

$$v_i = a_i S_i^{0.5} \qquad (3)$$

where a_i is a coefficient related to land use and S_i is the slope. Taking into consideration that the travel time through each cell is obtained by dividing the distance of travel within the cell by the travel velocity, the SDR can then be obtained as follows:

$$D_{R_i} = e^{\left(-\gamma \sum_{i=1}^{m} \frac{l_i}{a_i S_i^{0.5}}\right)} \quad (4)$$

where l_i is the flow length within the ith cell, and m is the number of cells along the flow path to the nearest channel cell. Their results suggested that the method is insensitive to the coefficient γ and therefore was assumed to be unity for simplicity.

SEDMOD

Fraser (1999) developed a conceptual model called Spatially Explicit Delivery Model (SEDMOD). SEDMOD operates within ARC/INFO and uses AML coding language and GRID raster modeling package and calculates spatially distributed delivery ratio for sediments that can be used in along with NPS pollution loading models such as the USLE. SEDMOD provides a spatially distributed estimate of the delivery ratio rather than a lumped estimate for the entire watershed, utilizing readily available data including DEMs, soil and land cover data.

The approach is based on estimating six parameters for each grid cell. Each parameter value is scaled using either empirical relationships from the literature or a hypothesized relationship with delivery potential. A composite layer is then created by combining the variables using linear weighing (Fraser, 1999). The variables used are: flow-path slope gradient; flow-path slope shape; flow-path hydraulic roughness; stream proximity; soil texture; and overland flow (soil saturation index). The first four variables describe the flow-path characteristics whereas the last two factors describe the source characteristics. The linear weighing is left up to the user to decide on what weight each variable gets and weights should add up to one. The delivery ratio is then multiplied by the sediment loss estimates obtained through the application of the USLE for each cell and the sediment yield for the watershed is simply the summation of individual cell sediment yields.

RESULTS

All method were applied to Stroubles Creek Watershed which is near Blacksburg, Virginia. A single interval storm with uniform rainfall was used. Resulting spatial distribution of SDR was compared visually.

The results of this preliminary analysis showed that the cumulative time ratio method produced a map of SDR that is a close reflection of the land use map as shown in Figure 1. Even though this behavior was not initially anticipated, it only follows correct intuition that dividing two cumulative times by each other will reflect the major difference used to estimate those two time. In our case, the determinant factor was land use (Manning's n).

The method of estimating SDR adopted by Jain and Kothyari was applied using a single time interval with a uniform amount of excess rainfall. The results are shown in Figure 2. The SDR as predicted by J-K method showed a very clear trend of association between higher SDR values (lighter shades) and proximity to streams. As this is an expected behavior that is documented in

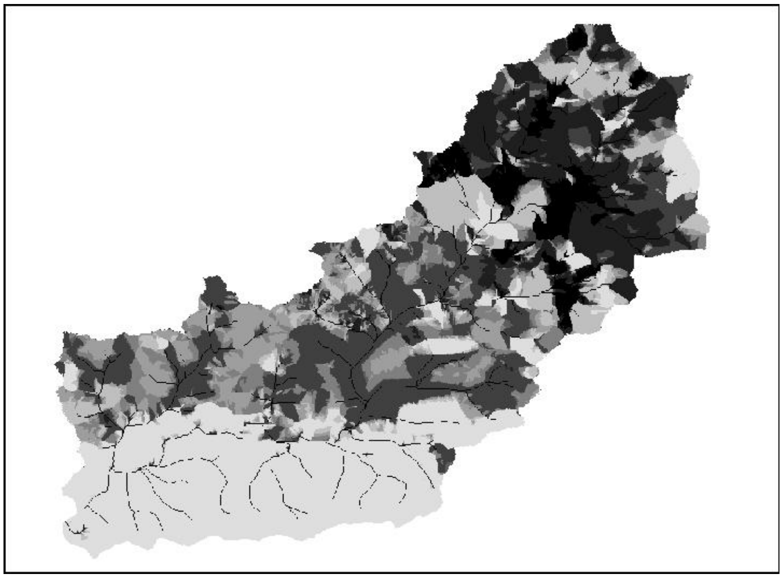

Figure 1. Sediment delivery ratio using the CTR method applied to Stroubles Creek Watershed. Lighter shades indicate higher sediment delivery ratios.

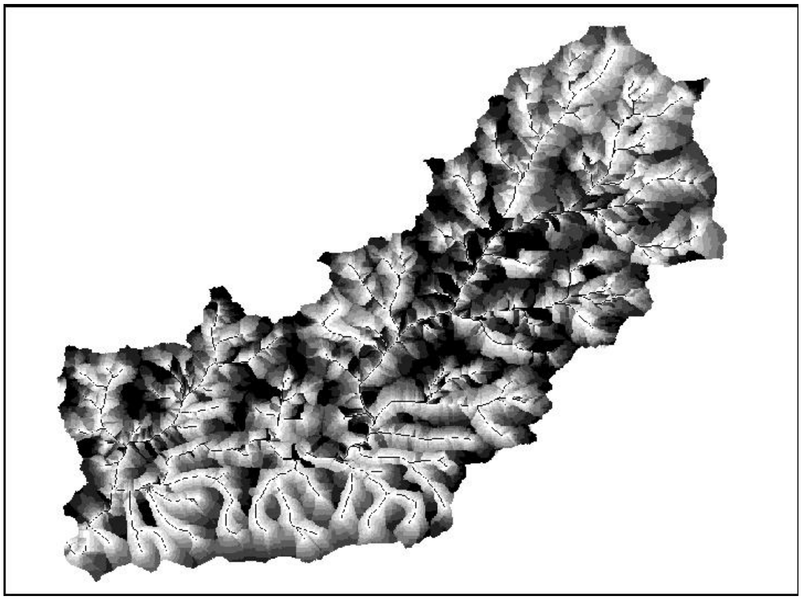

Figure 2. Sediment delivery ratio using the J-K method applied to Stroubles Creek Watershed. Lighter shades indicate higher sediment delivery ratios.

the literature, it seems that this method puts very low emphasis on the type of land use. Moreover, this method does not include any factor that would take into consideration the effects of soil type. Soil type is expected to play a role in determining the SDR since finer soil fractions travel longer distances and since different soils have different percentages of those fine sediments.

Finally, the SDR results obtained using the SEDMOD procedure followed a similar but not identical behavior as that obtained using Jain-Kothyari method. One of the six parameters used in the SEDMOD approach was the flow-path hydraulic roughness as represented by Manning's roughness coefficient. The SEDMOD approach suggested using the average flow-path roughness for each cell as the summation of all Manning's n coefficients divided by the number of cells along the flow path. The SEDMOD procedure proposed using this factor the same way the flow-path slope gradient was used. However, this approach seems to be erroneous in the sense that those two factors influence the sediment yield in opposite ways. While sediment yield increases as the average slope increases, it decreases as the hydraulic roughness increases. Therefore, two scenarios were evaluated, the first with hydraulic roughness proportional to sediment yield (as proposed by Fraser (1999)) while in the second scenario, the inverse of the hydraulic roughness was used. Figures 3 and 4 show the results of the first and second scenario, respectively. It can be seen from the two figures that in the south-west area of the watershed (which is characterized by higher slopes and higher hydraulic roughness (forest land)) that when the influence of both higher slope and higher hydraulic roughness were increasing sediment yield, the SDR was higher over the entire forested area. However, when greater slope was acting against greater hydraulic roughness, the resulting SDR was more in line with the predicted behavior for the rest of the watershed.

CONCLUSIONS

Three alternative spatially distributed sediment delivery ratio (SDR) methods were evaluated. The evaluation process was preliminary and was strictly reliant on visual comparison of the spatial distribution of higher versus lower values of SDR. Two of the methods (SEDMOD, and Jain and Kothyari) resulted in predictions that were more consistent with expected behavior of sediment deliver where areas closer to streams had higher sediment deliver potential. The cumulative time ratio (CTR) method results show a higher sensitivity to land use that dominates over topographic factors. Moreover, the CTR method does not appear without reformulation to improve the balance in those factors.

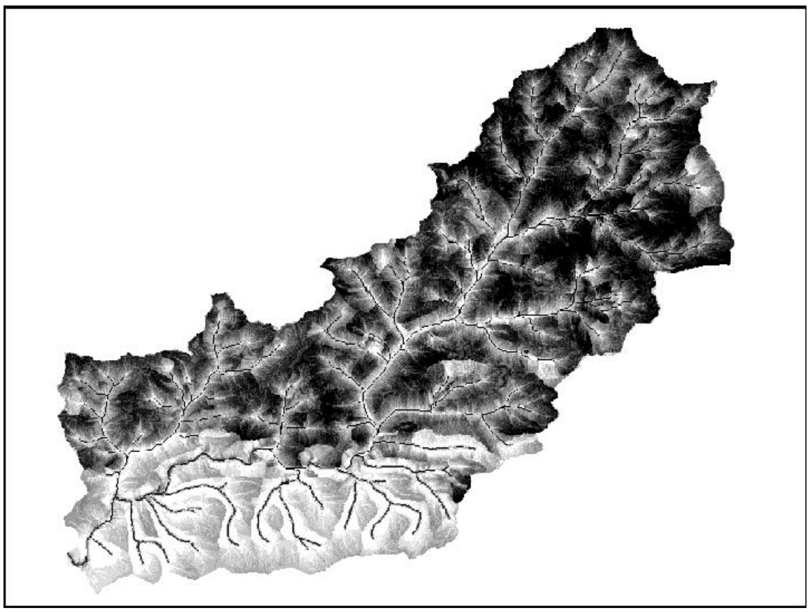

Figure 3. Sediment delivery ratio using the SEDMOD method. Here, SDR was *proportional* to hydraulic roughness. Lighter shades indicate higher sediment delivery ratios.

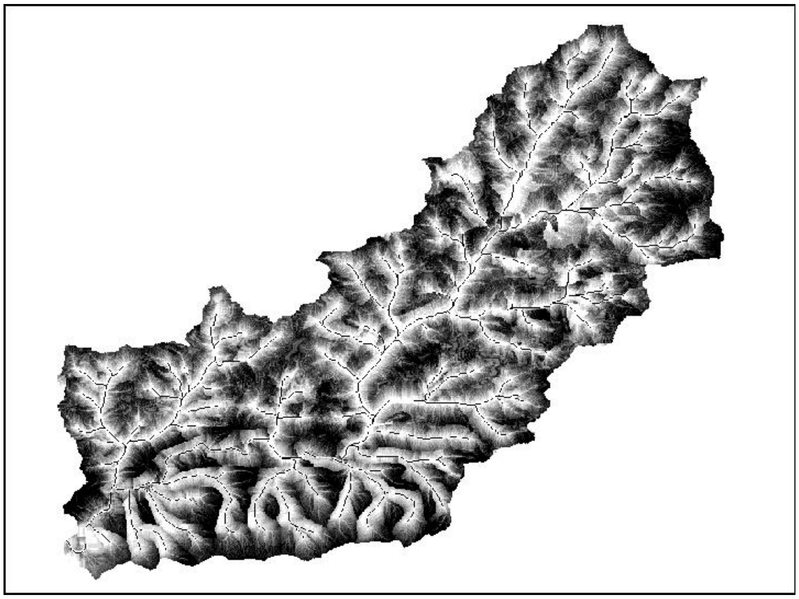

Figure 4. Sediment Delivery Ratio using the SEDMOD Method. Here, SDR was *inversely proportional* to hydraulic roughness. Lighter shades Indicate higher sediment delivery ratios.

It is expected that predictions of methods that account for the spatial location of erosion and sediment transport processes will prove more valuable than spatially lumped predictions provided by currently used models in TMDL. Accounting for those spatially varied processes can aid in the implementation phase of TMDLs since implementation requires site specific information which can be more accurately accounted for if methods used accounts for location.

FUTURE WORK

More spatially distributed sediment deliver methods will be studied. Moreover, the evaluation process in the future work will include comparing sediment yield with observed values as well as with predictions of widely used spatially distributed NPS models.

REFERENCES

1. Fraser, R.H.. 1999. SEDMOD: a GIS-based delivery model for diffuse source pollutants. New Haven, Conn., Yale University, Ph.D. dissertation, p. 76-99.
2. Jain, M. and U.C. Kothyari. 2000. Estimation of soil erosion and sediment yield using GIS. Hydrological Sciences 45 (5): 771-786.

3. Kothyari, U.C. and S. K. Jain. 1997. Sediment yield estimation using GIS. Hydrological Sciences 42(6):833-843.

4. Ree, W.O., F.L. Wimberley, and F.R. Crow. 1977. Manning n and the overland flow equation. Transactions of the ASAE 20(1):89-95.