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WEPP Simulated Tillage Effects on Runoff and Sediment Losses in a Corn-Soybean Rotation

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ABSTRACT

The Minnesota River is one of the 20 worst polluted rivers in the United States. Adoption of conservation tillage in the basin has been proposed as a way to achieve federally mandated 40% reduction in sediment concentration in the lower Minnesota River. A paired watershed study was undertaken to document the impact of tillage systems on runoff and sediment losses from landscapes in the lower Minnesota River Basin. In this paper, we present the validation of WEPP simulated tillage effects on runoff and sediment losses under a corn (*Zea mays* L.) -soybean (*Glycine max* L.) rotation. Thirty-year average runoff and sediment losses with CLIGEN generated climatic records were generally higher than using the historical climate records. CLIGEN generated runoff and sediment losses were significantly lower with chisel plowing compared to moldboard plowing. There was no effect of tillage in historical climate generated runoff losses but the sediment losses were significantly lower from chisel plowing than moldboard plowing. Average runoff with historical climate records was higher in soybean years than corn years, mainly due to two large events that occurred during the soybean years. There was no significant difference in average sediment loss between the corn and soybean years. It appears that climate plays a much more important role than other factors in determining runoff and sediment losses from these landscapes. Validation of the WEPP simulations against the field data showed that WEPP was able to predict the shape of relationships between the Control and the Treatment watersheds for both runoff and sediment losses. However, WEPP overestimated the absolute values of runoff and sediment losses compared to the measured values.

INTRODUCTION

Non-point source monitoring studies (1976-1992) have shown that approximately 566,875 tonnes per year of total suspended solids (78 20-tonnes truckloads per day) and 1,451 tonnes of total P are being transported by the Minnesota River at Fort Snelling in the Twin Cities (Minnesota Waste Control Commission, 1994). This is about 22 times and 3.6 times greater than that in the St. Croix and the Mississippi Rivers before the confluence with the Minnesota, respectively. Annual suspended-sediment loads in the Minnesota River at Mankato have varied from 0.2 to 3.3 million tonnes (Payne, 1994). Except for 1969, suspended sediment loads have generally been less than 2.0 million tonnes per year. This is equivalent to a sediment yield of 84.5 tonnes km^{-2} yr^{-1} or 525 kg ha^{-1} yr^{-1}. In 1969, the sediment yield was equal to 135 tonnes km^{-2} yr^{-1} or 840 kg ha^{-1} yr^{-1}.

The Minnesota Pollution Control Agency has suggested the use of conservation tillage practices that leave 30% residue cover as a way to achieve federally mandated 40% reduction in sediment load in the Minnesota River. Although it is well establish that 30% residue cover reduces soil erosion by about 65%, it is unknown how much of this would translate to reductions in sediment loading of the river. The objective of this study was to test the use of Water Erosion Prediction Project (WEPP) model as a way to evaluate the impact of conservation tillage practices on sediment delivery with a paired watershed approach. If this is successful, then the WEPP model will be an inexpensive and quick tool to evaluate the impact of climate and management practices on surface water quality leaving small watersheds in the Minnesota River Basin.

PROCEDURES

The WEPP model was tested on a paired watershed study located in Scott County, MN. The two watersheds cover an area of 1.67 ha and 1.10 ha. The crop rotation was a corn-soybean rotation. The tillage was fall chisel plowing after corn and spring field cultivation after soybean. The watershed monitoring commenced in 1996 and the first crop was soybean. The site was monitored using devices that allow automatic sampling of runoff water. This included two flumes in series to measure flow discharge; a nitrogen bubbler combined with a pressure transducer to measure flow depth; a data logger to store data on sample number, flow data, and weather parameters such as precipitation, temperature and humidity; and an automatic sampler to collects runoff samples and record sample timing. Water samples were taken at specified time interval, and, then, analyzed for solids and other non-point source pollutants. Other details of the set-up are given in Ranaivoson (1999).

WEPP Model Inputs

WEPP Watershed Model Version 97.3 was used for simulations. The main input files were climate, slope, soil, crop and the management practices. For watershed application, these input files were also supplemented with files on watershed and channel characteristics. The outputs from the model included runoff and sediment losses.

The two watersheds at Scott County were labeled as the

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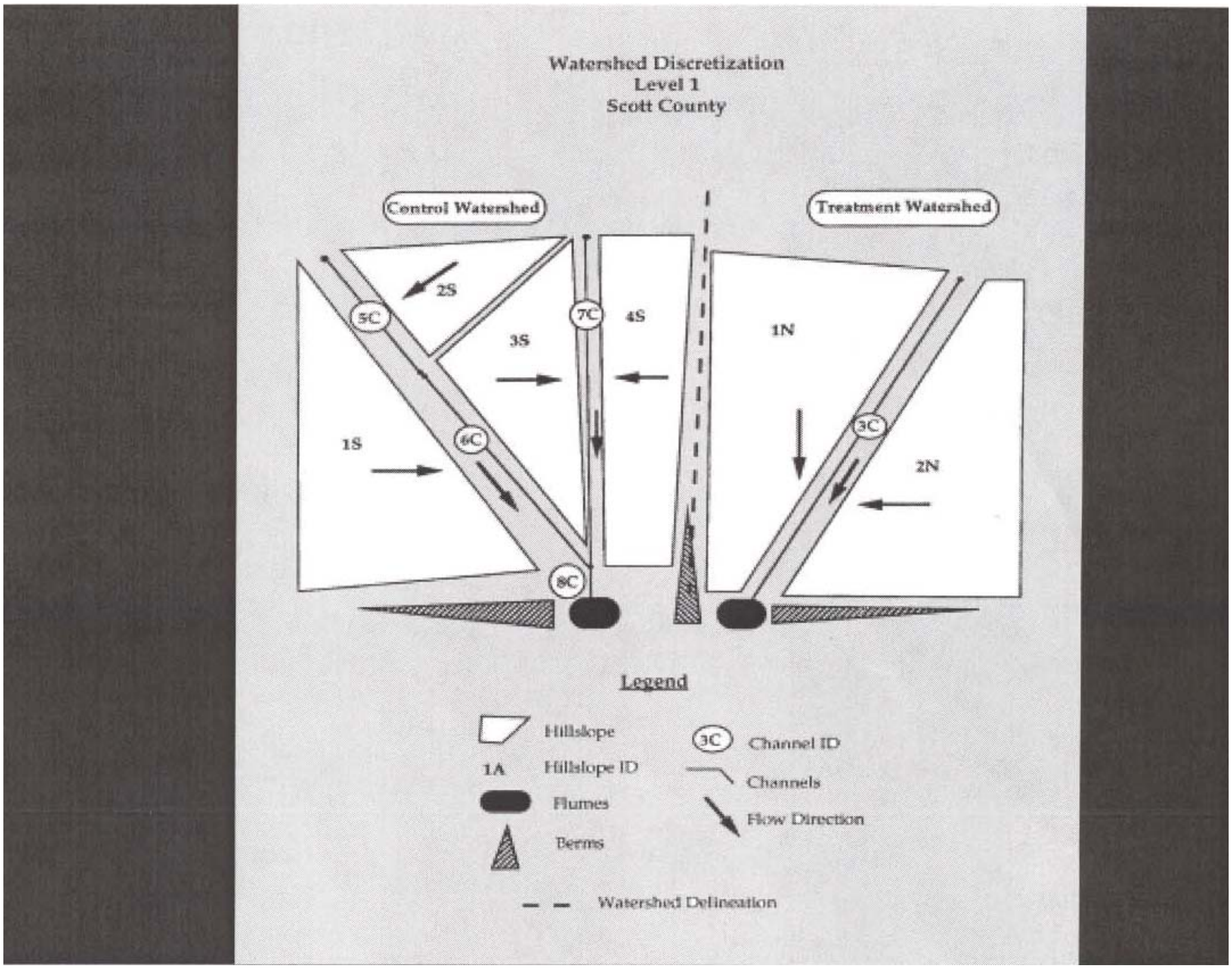

Figure 1. Paired watershed discretization for WEPP model.

Table 1. WEPP Simulation runs for paired watersheds

Calibration	Control, South	Moldboard
	Treatment, North	Moldboard
Treatment	Control, South	Moldboard
	Treatment, North	Chisel

Control and the Treatment watersheds. The Control watershed contained four hillslopes and two main channels that converge to a smaller channel before the outlet (Fig. 1). The Treatment watershed was divided into two hillslopes and one channel (Fig. 1). Runs needed to simulate a paired watershed scenario are given in Table 1. For a given variable (runoff or sediment), the regression curves between the Control and Treatment watersheds were generated for both the calibration and the treatment periods.

Climate Inputs

For Scott County watersheds, the historical climate records were taken from the Minneapolis-St. Paul International Airport. The simulated climate records were internally generated in the WEPP using the CLIGEN subroutine.

Soil Inputs

Soils in the Scott County watersheds were dominated by Clarion silt loam, a very deep, well-drained, moderately permeable soil (fine-loamy, mixed, mesic typic Hapludolls). The other soil types include the following: Lester loam (fine-loamy, mixed, mesic Mollic Hapludalfs) and LeSueur clay loam (fine loamy, mixed, mesic Aquic Argiudolls) complex; an association of Webster clay loam (fine-loamy, mixed, mesic Typic Endoaquolls) and Glencoe clay loam (fine-loamy, mixed, mesic Cumulic Endoaquolls). Clarion, LeSueur, and Lester soils were located in the Control Watershed whereas the Clarion and an association of Webster-Glencoe were located in the Treatment watershed.

Watershed Characteristics

The watershed characteristics such as hillslope area and width, slope value, slope orientation, were obtained from the surface elevation data using the Terrain Analysis Program for the Environmental Science-Grid (TAPES-G), Surface Hydrological Analysis of ARC/INFO, and SURFER.

Plant/Management Inputs

The crop and tillage management inputs were related to the corn-soybean rotation (soybean first year). For the calibration period, field operations for soybean were spring field cultivation, planting of drilled soybeans, harvesting, and fall moldboard plowing, in that order. Field operations for corn were spring field cultivation, planting with double-disk openers, harvesting, and fall moldboard plowing, in that order. For the treatment period in the Control watershed, field operation sequences remained the same for corn and soybean as described previously. However for the Treatment watershed during the treatment period, the field operation sequence for soybean was spring field cultivation, planting of drilled soybean, harvesting and no fall tillage. For corn, the field operation sequence was spring field cultivation, planting with double-disk openers, harvesting, and fall chisel plowing. The main crop growth parameter was adjusted to reach the farmer's target yield of 9.4 Mg ha^{-1} for corn and 3.4 Mg ha^{-1} for soybean.

WEPP Watershed Simulations

This input file for watershed simulations included the relative position of the (1) hillslopes in the landscape, (2) the channel network, (3) impoundment location, if any, and the connections of each element to other elements in the watershed.

RESULTS AND DISCUSSIONS

The first set of simulations were run for a 30-year period either using the CLIGEN climate generator or the historical climate records. The three simulation runs were: the Control watershed under moldboard plowing (CWM), the Treatment watershed under moldboard plowing (TWM), and the Treatment watershed under chisel plowing (TWC). In the paired watershed analysis, the relationship between the first two runs (CWM & TWM) defines the calibration period whereas the relationship between the first and the third runs (CWM & TWC) defines the treatment period. Comparison of regression relationships between the calibration and the treatment periods then quantifies the effect of treatment (in this case chisel plowing) on runoff and sediment losses.

Simulations with CLIGEN

The daily rainfall depth generated with CLIGEN ranged from 0.3 to 120 mm over the 30 year-period. The yearly average for the generated database was 715 mm. The total number of storms for the 30-year period was 3,305. Out of these only 330 individual storms generated runoff and sediment losses.

The regression relationships for runoff losses between the Control and the Treatment watersheds both for the calibration and the treatment periods only showed a significant difference in their intercepts. The two lines appear to converge at high runoff values, thus suggesting that large events produced almost the same amount of runoff in both periods. The overall effect in the treatment period was a slight downward displacement of the regression line while the two lines remained nearly parallel. Geometric average runoff from the Treatment watershed under moldboard tillage was 2.79 mm and this value decreased to 1.49 mm, an equivalent of 47%, under chisel plow conditions. This decrease was associated with the presence of more crop residues in a chisel tilled soil which reduce surface sealing, increase infiltration, and in turn reduce soil detachment due to raindrop impact.

Sediment losses during May and June were equivalent to 66%, 68%, and 58% of the annual losses for the CWM, TWM, and TWC conditions, respectively. July and August together accounted for an additional 21%, 24%, and 25% of the annual sediment loss for the CWM, TWM, and TWC conditions, respectively. The regression relationship for sediment loss between the Treatment and the Control watersheds both during the calibration and treatment periods showed a downward displacement in the regression line during the treatment compared to the calibration period. This downward shift in the treatment curve was due to the presence of surface residue cover, once chisel tillage system was implemented in the Treatment watershed.

Simulation with Historical Climate Records

The rainfall amount for the 30-year historical records ranged from 0.3 to 232 mm. The 30-year average rainfall was 721 mm. The month of June had the highest rainfall in this 30-year period followed by August, July, and May, in that order. The total number of runoff events during the calibration period were 115 compared to 103 during the treatment period. More than 80% of the runoff events had <10 mm runoff losses. The two largest events in the 30-year period produced 34%, 31%, and 38% of the total runoff under CWM, TWM, and TWC conditions, respectively. Runoff losses were the largest in July followed by June, August, and May, in that order. The covariance analysis of the runoff regression lines between the Treatment and the Control watersheds both for the calibration and treatment periods showed that neither intercepts nor slopes were significantly different for the two periods. This means, changing tillage system had little effect on runoff volume.

Overall, the sediment yield varied from 0.0 to 30.1 T ha^{-1}. Events that produced less than 2 T ha^{-1} accounted for 21.5%, 26.1%, and 46.7% of the total sediment losses for the CWM, TWM, and TWC conditions, respectively. For the CWM and TWM conditions, June, July, May, and August, in that order, produced the most sediment. However the sediment loss for the TWC treatment followed the order: July>June>August>May. Changing tillage from moldboard plow to chisel plow in the Treatment watershed decreased the sediment loss by 61%. The covariance analysis of the regression lines for both the calibration and the treatment periods showed that slopes and intercepts of both lines were significantly different from each other at p=1%.

A comparison of the 30-year simulations using historical or CLIGEN climate records showed that historical climate records generated a lower number of sediment loss events per year (4) compared to the CLIGEN generated climate records (10). Irrespective of the type of climate records (historical or CLIGEN), the covariance analysis showed the same level of significance in sediment loss when moldboard plowing was replaced with chisel plowing in the Treatment watershed. With CLIGEN climatic records, the 30-year average runoff and sediment losses decreased (89 to 69 mm and from 15.5 to 7.5 Mg ha^{-1}, respectively) when moldboard tillage system was replaced with chisel plow system. With the historical climatic records, there was no difference in runoff losses but the 30-year average sediment loss decreased from 3.8 to 1.4 Mg ha^{-1}when the moldboard tillage system was replaced with chisel tillage system.

Runoff and Sediment Losses in Corn vs. Soybean Year

Since in a corn-soybean rotation, the residue type and cover is different in the corn vs. the soybean year, we further analyzed the effect of corn vs. soybean residue cover on simulated runoff and sediment losses using the historical climate records. Residue cover in the soybean year was from previous year's corn. Conversely, residue in corn year was from previous year's soybean.

Soybean year

In the 15 soybean years, there were a total of 50 runoff and sediment loss events, equivalent to 43% of the total number of events in the 30-year simulation period. During the calibration period, total runoff delivered at the outlet did not differ significantly between the CWM and TWM watersheds (571 mm and 562 mm). However during the treatment period, TWC conditions reduced runoff by 16% compared to the TWM conditions. Runoff losses in July and August were equivalent to 76%, 74%, and 84% of the annual runoff losses from CWM, TWM, and TWC treatments, respectively. These high runoff losses were due to two major events that occurred in August 1977 and July 1987. These two events generated 57%, 54%, and 64% of the 15-year period total runoff from the CWM, TWM, and TWC treatments, respectively.

Compared to moldboard plow based tillage system, the chisel plow based tillage system decreased the sediment loss by 56% from the Treatment watershed. The two large events in August 1977 and July 1987 together produced 55%, 59%, and 73% of the 15-year total sediment losses from the CWM, TWM, and TWC treatments, respectively. Although, May and June are usually the months when the ground is bare and susceptible to erosion and runoff losses (because of minimal protection following secondary tillage and absence of crop canopy), large events in July and August eroded the soil surface in spite of canopy protection.

Corn Year

In the 15 corn years, there were a total of 65 events. These events represented 56% of the total number of events in the 30-year simulation period using the historical climate records. During the calibration period, total runoff losses from the CWM were slightly lower (399 vs. 424 mm) than that from the TWM. Compared to moldboard plowing, implementation of chisel plowing decreased runoff losses from the Treatment watershed by an average of 23%.

June and May, in that order, produced the highest sediment loss for the corn years. These two months produced 82%, 80%, and 69% of the annual sediment yield for the CWM, TWM, and TWC conditions, respectively. These two months usually presents a greater erosion risk than the rest of the year for at least two reasons: (1) secondary tillage operations decrease residue cover, and (2) the canopy cover is not large enough to protect the ground surface.

Validation of Simulated Runoff and Sediment Losses

The WEPP model was validated on Scott County watersheds from 1996 through 1998. Here we report the validation test for 1997 data set. All WEPP simulations were run with the higher-level watersheds discretization than shown in Fig. 1.

Runoff

In 1997, a total of seven runoff events (one snowmelt event and six rainfall events) were recorded in the field. Total runoff measured in the field was 47.7 mm and 77.9 mm for the Control and Treatment watersheds, respectively. The snowmelt event occurred from March 20 to 28, 1997 and resulted in a total runoff of 35.6 mm and 76.5 mm from the Control and the Treatment watersheds, respectively. Four out of six rainfall events occurred in April and May. Total runoff in April was 0.05 and 0.039 mm from the Control and the Treatment watersheds, respectively. Three rainfall events occurred during May (13, 16, and 22) resulted in runoff losses of 0.023 and 0.143 mm from the Control and the Treatment watershed, respectively. One rainfall event (6.10 cm) on July 25, 1997 produced 11.1 mm of runoff from the Control watershed. However, data from the Treatment watershed on this date was lost due to equipment malfunction. Another rainfall event (6.81 cm) on August 19, 1997 produced 0.87 mm and 0.71 mm of runoff from the Control and the Treatment watersheds, respectively. The last rainfall event in 1997 occurred on September 15 and produced a runoff of 0.06 mm and 0.12 mm from the Control and the Treatment watershed, respectively.

In comparison to field measurements, the WEPP model simulated 9 runoff events compared to 7 events measured in the field. The total simulated runoff was 44.4 mm and 50.4 mm from the Control and the Treatment watersheds, respectively. WEPP simulated snowmelt in three separate events during January and February were 23.2 mm and 26.1 mm for the Control and the Treatment watersheds, respectively. Four (4/4/97, 7/25/97, 8/19/97, 9/15/97) of the nine WEPP simulated events coincided with those recorded in the field. WEPP simulated runoff was lower than the measured value in the first event (4/4/97), very close in the second event (7/25/97), and higher in the two last events (8/19/97, 9/15/97). The two extra events simulated by WEPP occurred on 6/24/97 and 8/14/97. WEPP simulations missed a series of field runoff on May 13, 16, and 22.

The field measurements showed that in 1997, snowmelt contributions to total runoff were much greater (about 75%) than those from rainfall runoff. In contrast, WEPP simulations showed that the contributions of both snowmelt and rainfall to total runoff were nearly equal (52 % vs. 48%). Total runoff in 1997 from WEPP simulations and field measurements were 44.4 mm vs. 47.7 mm for the Control watershed, and 50.4 mm vs. 77.9 mm for the Treatment watershed.

Detail analysis showed that the discrepancy between the WEPP simulated and the field measurements was partially because (1) the snow density (350 kg m^{-3}) and air temperature (>-3°C) criteria in the WEPP for the start of snowmelt runoff may too high and too low, respectively; (2) the process of lumping several small rainfall bursts during a day into a one single daily rainfall event increased the probability of runoff thus overestimating runoff and sediment losses; and (3) a discrepancy in timing of tillage operations between simulations and the actual field operations.

Sediment Losses

There were three events that produced sediment losses in 1997. The total measured sediment losses were 0.74 Mg ha^{-1} and 0.85 Mg ha^{-1} from the Control and Treatment watersheds, respectively. Snowmelt associated sediment losses occurred from March 20 to 28 and were 0.055 Mg ha^{-1} from the Control watershed and 0.180 Mg ha^{-1} from the Treatment watershed. A rainfall event on July 25 also produced 0.093 Mg ha^{-1} of sediment from the Control watershed, however, sediment data from the Treatment watershed on this date was lost due to equipment malfunction. The second rain on August 19, 1997 generated 0.004 Mg ha^{-1} of sediment from the Control watershed and 0.003 Mg ha^{-1} from the Treatment watershed.

In comparison to field measurements, WEPP simulations in 1997 resulted in more than 1 Mg ha^{-1} of sediment loss from each watershed during the snowmelt event. The rainfall event on July 25 simulated almost 3 Mg ha^{-1} of sediment loss from each watershed. The second rainfall on 8/19/97 simulated in excess of ten times more sediment production compared to the field measurement. The total simulated sediment losses in 1997 were 4.5 Mg ha^{-1} and 4.2 Mg ha^{-1} from the Control and Treatment watersheds, respectively.

Covariance analysis of runoff showed that neither slope nor intercept were statistically ($p = 0.89$ and $p = 0.96$, respectively) different between the control and the treatment periods. Similarly, the slope and intercept of the sediment loss relationship between the Treatment vs. Control watersheds were also not statistically ($p = 0.86$ and $p = 0.13$, respectively) different. The WEPP model was nicely able to simulate tillage effects on runoff sediment losses in a paired watershed design, however, the absolute amounts of runoff and sediment losses were much higher than the measured values. Improvements in WEPP simulation algorithms are needed for simulating snowmelt events and for conditions when there are several bursts of rainfall on any given day with no rainfall in between.

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