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BIOGEOCHEMICAL ANALYSES OF SOILS IN CLEAR CREEK, IOWA

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ABSTRACT

This paper reports the results of soil biogeochemical analyses (e.g., organic matter, % of clay, % of sand, CEC, pH, etc.) performed to characterize the biogeochemical properties of soils in the Upper South Amana area, a sub-catchment of the Clear Creek Watershed. Most of these properties are in turn used as inputs to the WEPP (Water Erosion Prediction Project) upland erosion model to predict sediment erosion rates. WEPP is a process-based, event-based, distributed parameter, water flow driven erosion prediction model. Climatic data and Digital Elevation Models (DEM) are also incorporated in the model along with the biogeochemical properties of the soils. The WEPP model is first calibrated and then a sensitivity analysis is performed to identify the governing parameters of upland erosion in the Upper South Amana Area. Such comparison will further strengthen the argument regarding event-based simulations vs. continuous based simulations. The results of this study will be used for supplementary investigation of physical mechanisms of upland erosion processes.

1. INTRODUCTION

Watershed processes have been mainly examined independently from each other. Recently, there is an attempt to link all processes and examine their independence in order to provide holistic approach for Total Maximum Daily Load (TMDL) purposes and non-point source prediction. Every year, approximately 75 billion tones of soil are removed from lands that are mainly agricultural due to wind and water erosion. The annual cost of erosion in the United States has been estimated as $44 billion and nearly $400 billion worldwide (Pimental et al., 1995). Other than reservoir filling, pollution transportation and consuming arable lands, as Al-Kaisi (2000) states, the impact of soil erosion on water quality becomes significant, particularly as soil surface runoff. To effectively control erosion and minimize its water quality impacts, we need to know the spatial and temporal characteristics of the erosion processes, how soils are transported and deposited, how the changing landscape conditions interact with different rainfall patterns, how cover crops and soil amendments affect runoff water quality, and more importantly, how agricultural chemicals and nutrients are transported in surface runoff during erosive events. (The National Soil Erosion Research Laboratory, 2002) In this paper, a numerical model of upland erosion WEPP, and a literature-based reasoning of the relationship between soil biogeochemical characteristics and soil erosion are presented. The WEPP model is considered here for the following reasons: it has a process-based and highly detailed structure, it is event-based and distributed parameter, it predicts water flow driven erosion and also it is well reviewed and critiqued.

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Other than inputs to the WEPP model, biogeochemical properties provide an additional tool for tracing sediment origin. The biogeochemical properties can be classified into 3 categories viz., geological, chemical and biological. Geological factors contributing to spatial variability in erosion and sediments are topography, soil type, composition and water detention capacity (amount of water trapped in the pores of the soil). Chemical factors include pH, Cation Exchange Capacity (CEC) trace metals, etc. Weathering is a major H+ consuming process and pH-buffering mechanism, not only globally and regionally but it also plays a major role in local watersheds in soil processes, in nutrient uptake by plants and in epidiagenetic reactions in sediments (Stumm, 1998). Biological parameters, which affect the soil significantly, are the vegetation type, microbial mechanisms and organic matter. Vegetation (Flora) and organisms (Fauna) physically churn the soil and help stabilize soil structure (Brady, 1984). Thus, evaluating soil-plant relations is a valuable tool for understanding and predicting long-term variability associated soil conditions. Analysis of the photosynthetic pathway (C4 or C3) of the plants was considered as different plants affect organic C and N (or %C & %N) and also the type of microorganism.

2. OBJECTIVES

The aim of this study is to characterize the geological, chemical and biological, properties of the Upper South Amana sub-catchment soil and relate the biogeochemical soil characteristics with soil erodibility and sediment transport. The biogeochemical properties obtained are used as inputs to the upland erosion model (WEPP) to predict the highly erodible areas and recommend some necessary precautions. A comparison of WEPP with other upland erosion models and a contrast of single storm simulations with continuous simulations are briefly discussed. The results of this study will provide valuable information in the near future for verification of a unique fingerprinting technique which uses the stable nitrogen and carbon isotopes, $\delta^{15}N$, $\delta^{13}C$, and the carbon to nitrogen atomic ratio, C/N as eroded source soil-sediment tracers.

3. STUDY SITE

The Clear Creek Watershed is primarily agricultural, with 60% of land cover being row crops and about 20% in pasture/hay. The remaining 20% represents other landuses (roads, floodplains) and lands placed under the NRCS CRP. The average annual precipitation within the Upper South Amana region is approximately 35 inches/yr. (SCAS, Oregon State University, 2000) Average daily temperature, recorded from 1961 to 1990, is about 50 ^{o}F with an average July maximum of 85 ^{o}F and an average January minimum of 8 ^{o}F. (NCDC Data for 1961-1990) Upper South Amana sub-catchment is prone to highest erosion rates mainly due to steeper hillslope gradients and higher density of farm lands. The average gradient of the hillslopes along the sub-catchment is 4%, ranging from 1% to 10% approximately. The lowest and highest elevations within the sub-catchment are 770 ft and 900 ft, respectively.

There are four main soil associations throughout the sub-catchment; Otley-Ladoga-Clinton (OLC), Ladoga-Otley-Adair-Shelby (LOAS), Colo-Bremer-Nevin-Nodaway (CBNN) and Tama-Downs-Shelby (TDS) associations with CBNN around the creek boundaries, TDS occupying the northern half of the sub-catchment, LOAS occupying the southern half of the sub-catchment and OLC located at the high center portion. Most of CBNN formed from sediments that were deposited on the flood plains and OLC formed from loess on uplands. Both LOAS and TDS formed from loess and glacial till on uplands. All four associations serve well for farming purposes and are moderately rich in organic matter (about 3 ~ 4%). The dominant soil type within the sub-catchment is silty clay loam.

4. METHODOLOGY

4.1 Sample Collection and Laboratory Investigation

Tests Five reference soils of the South Amana sub-watershed were considered. The sample locations had an elevation of 700-900 ft and latitude and longitude of N 41^{o} 44' and W 91 ^{o}55' respectively (obtained via GPS). Atmospheric and soil temperatures noted during sampling were in the range 25-30^{o}C and 12-18^{o}C. Here conventional crops chosen to classify the land-uses are viz., corn, soybean and conservation reserve program (CRP) grass. Slope aspects selected are the floodplain and the banks of the creek. Random soil samples in a field moist condition were collected from each of these distinctive land-use locations to a depth of 0-5 cm. These samples gave a good representation of the spatial variation of the biogeochemical properties. Samples presented here were taken on November 2005.

The field moist soil samples were oven-dried at 55-60^{o}C and dried samples were soaked in sodium hexametaphosphate ($(NaPO_3)_6$) to separate flocculated particles prior sieving. Geological tests of importance included determination of liquid and plastic limit, particle size distribution, soil composition and water content. Particle size and soil composition were analyzed with sieve and hydrometer analysis. Water content was estimated using the difference between weights of the field-moist and oven-dried soil. The liquid and plastic limits were determined using the Casagrande liquid limit device. The procedures listed for geological tests follow ASTM standards. Chemical properties tested include of pH, cation exchange capacity (CEC), Sodium Adsorption Ratio (SAR), some DTPA Micronutrients (Fe, Zn, and Mn), organic matter, total C & N, nitrate-N (NO_3-N) and Ammonia-N (NH_4-N). Soil pH was determined by making a suspended soil solution (1:1 ratio of soil: distilled water) and measuring the pH. Exchangeable cations were determined adopting NH_4-OAc extraction method, which uses ICP Spectrometer. Later, CEC was estimated as the sum total of exchangeable cations adsorbable by the porous medium; expressed in mol/kg. SAR was calculated as a measure of relative abundance of Na^{+} to the other two most common cations Ca^{++} and Mg^{++} (Ariathurai et al., 1978). Micronutrients Fe, Mn, Zn are extracted with the chelator DTPA and analyzed by Flame Atomic Absorption. Soil samples were subjected combustion to find out the total C & N in the Leco TrueSpec C-N analyzer, later organic matter was calculated. Biological study involved data collection on the type of photosynthetic pathway of the plants to name the contribution of vegetation to the spatial variation.

4.2 Numerical Modeling

Empirical watershed models (e.g. USLE, RUSLE and AGNPS) are based primarily on field observations and as a result they are usually applicable to the same conditions for which their parameters have been calibrated. Physically process based models like WEPP do not comprise this weakness and have a wider range of application. WEPP is a dynamic model, which simulates climate and plant growth during the simulation period. One of the most important attractions of WEPP is its spatial and temporal modeling flexibility. The WEPP model can be used in both hillslope and watershed applications for both single storms and continuous simulations. The maximum field size that has been verified with measurements and thus recommended is about 640 acres. The WEPP model includes components for weather generation, frozen soils, snow accumulation, snow melt, irrigation, infiltration, water balance, overland flow hydraulics, plant growth, residue decomposition, soil disturbance by tillage, consolidation, erosion and deposition. It can simulate various Best Management Practices (BMP) including agricultural practices (e.g. drainage, tillage, contouring), terraces, ponds, culverts and etc. The hillslope component of the

WEPP erosion model requires mainly 4 input data to run: climate data (meteorology data, precipitation, wind, temperature, dew point etc.), slope data, soil data (soil type, texture, porosity, conductivity, OM, CEC, Albedo, number and depth of soil layers), and plant/management data (plant types, characteristics, growth parameters, management practices, etc.); while the watershed simulation requires the 4 hillslope inputs plus watershed structure information (hillslope and channel arrangement). The results of the WEPP model include estimates of precipitation, runoff, soil loss, soil deposition, sediment yield from hillslopes and channel segments. Precipitation estimates are obtained via a stochastic weather generator called CLIGEN.

The sub-catchment of interest is simulated for three single storms within 2004-2005 and for 2 years (2004-2005) of continuous corn-soybean rotation period. As Oduro et al. (1997) states, single storm simulations are important because a few intense storms are responsible for most of the annual erosion. In addition, single storm simulations are easier to verify via field measurements time wisely and they provide valuable calibration information which might be later used for continuous simulations. A single storm model simulates the duration of a storm which may range from a few hours to a few days. Continuous simulations are important as they provide valuable information about the order of average annual soil loss and also a feeling of highly erodible areas within the watershed. A continuous model simulates a longer period, predicting watershed response both during and between precipitation events. Single storm simulations' being highly sensitive to initial conditions makes preliminary field investigation much more vital prior to single storm simulations as the effect of initial conditions diminish by time in case of continuous simulations. Single storm models do not have the capacity to accurately characterize erosional response of the complex and dynamic erosional system (Nearing, 2004).

4.3 Data Acquirement

Empirical In order to avoid misleading results from the numerical model, data acquirement is achieved with great attention. Land management data is obtained through personal contact with Steve Johnston and Ruth Izer, USDA-NRCS, Williamsburg, IA. Observed climate data is obtained from Daryl Herzmann, currently the Program Assistant for the Iowa Environmental Mesonet (IEM) at Iowa State University (ISU) in Ames, Iowa. The IEM collects environmental data from cooperating members with observing networks. For topographical information, the USGS National Elevation Dataset (NED) is used. The NED is a mixture of best-available elevation data. WEPP required soil data is obtained here primarily by field measurements and laboratory analyses. For verification previously published soil survey reports of Iowa were used. The soil surveys were digitized by the Iowa Cooperative Soil Survey (ICSS), which includes the USDA NRCS, the Iowa Department of Agriculture and Land Stewardship, and ISU, Cooperative Extension Service and Iowa Agriculture and Home Economics Experiment Station. The township-level data was joined and dissolved to county-wide coverage, and converted into a state-wide GRID by the Iowa DNR, Geological Survey. In order to attain the required soil parameters, the digitized soil maps were linked to the Iowa Soil Properties and Interpretations Database (ISPAID).

5. RESULTS AND DISCUSSIONS

5.1 Laboratory Results

The results of biogeochemical characteristics analyzed in the laboratory for 5 source soil samples are as shown in the Table 1.

Table 1 Biogeochemical characteristics of Upper South Amana soil.

Property	Units	Sources				
		Corn	**Soybean**	**CRP**	**Floodplain**	**Bank**
Geological						
Silt	%	65.4	59.2	63.3	70.0	66.4
Clay	%	29.5	34.7	30.3	26.4	26.7
Sand	%	5.10	6.10	6.40	3.60	6.90
Water Content	%	21.5	20.0	25.36	16.1	18.35
Specific Gravity	---	2.56	2.73	2.46	2.54	2.50
Plastic Limit	%	26.70	27.00	24.20	32.35	24.36
Liquid Limit	%	36.34	38.07	38.59	47.00	37.68
Chemical						
pH	---	7.70	7.75	6.05	6.45	6.95
Buffer pH	---	7.30	7.35	6.70	7.00	7.13
Exch. K	cmol/kg	0.749	0.639	0.431	1.154	0.248
Exch. Ca	cmol/kg	21.21	31.13	10.82	12.52	12.00
Exch. Mg	cmol/kg	3.63	3.26	2.18	3.36	2.98
Exch. Na	cmol/kg	0.07	0.10	0.05	0.03	0.04
Zn	g/kg	0.0021	0.004	0.0011	0.0052	0.0016
Fe	g/kg	0.070	0.098	0.116	0.140	0.088
Mn	g/kg	0.013	0.010	0.018	0.021	0.017
Organic Matter	g/kg	43.55	54.85	53.85	74.70	30.52
Total C	g/kg	23.85	30.05	29.59	40.96	16.71
Total N	g/kg	2.061	1.964	2.672	3.496	1.638
NO_3-N	g/kg	0.0036	0.0022	0.0026	0.0027	0.0038
NH_4-N	g/kg	0.0013	0.0140	0.0040	0.0050	0.0080
CEC	cmol/kg	25.660	35.120	17.089	17.069	15.266
SAR	√(cmol/kg)	0.0191	0.0236	0.0205	0.0123	0.0135
Biological						
Photosynthetic Pathway	---	C4	C3	C3	---	---

Categorizing each soil, it can be seen that the corn site soil, though similar to soybean site soil has characteristic values slightly higher among the cultivated soils, but floodplain soil (uncultivated) has highest characteristic values compared to all types of soils. Higher water content among the samples is seen for CRP - 25.4% & corn soil - 21.5%. This can be explained by the vegetation cover, which retains infiltration i.e., root spread of grasses in the topsoil compared to corn. In another way we can also say the evapotranspiration process is low in smaller plants (grasses) thus preventing water loss due to canopy height. Legumes and grasses are next after forests in effectiveness of their dense covers. Row crops such as corn, soybeans and potatoes offer relatively little cover during the early growth stages and thereby encourage erosion (Brady, 1984). Sieve and hydrometer analysis show that clay for corn, soybean and CRP are 29.5%, 34.7% & 30.3%, whereas that of floodplain and banks are 26.4% & 26.7. Dependence of erodibility on the soil composition is significant. In soils with clay content >40%, the clay acted as a cementing material which stabilized the aggregates against disintegration by slaking and the impact of raindrops. In soils with 20-40% clay, clay content was sufficient to produce a fully developed seal, but not to make the aggregates stable against breakdown by wetting and raindrop impact; thus maximum runoff was produced (Ben-Hur et al.,1985). Atterberg's values accord with the concept that water is more apt to flow out of wet soil than from one low in moisture (Brady, 1984). This relates erosion to strength of soil particle bonding and weakening of this bond due to water particles. More water it can withhold, denser the soil tends to be and thus lower shear required for soil erosion. Soil pH of both cultivated soils was in the neutral range, linking to crop sustained nutrient balance. Variations in soil pH were obtained in different tillage systems as a consequence of variations on clay and organic matter content. pH values for the CRP, floodplain and bank soils lie in the range of 6.0-7.0, which though neutral are reported to lie in the range in which particles are most susceptible to erosion due to point to point contacts between clay particles. Initial erosion rates were higher at intermediate pH conditions from pH 5.5-7.0, at a pH of 6.0, there was an abrupt decrease in critical stress and the erosion rate coefficient (Ravisangar et al., 2001).

Cation exchange for the corn and soybean soils were among the highest (25.7 and 35.1 cmol/kg), indicating liming to sustain neutral pH fertilizer application, making these soils more stratified with clay, whereas the uncultivated soils have lower CEC values (15.3 – 17.1 cmol/kg). Increasing amount of clay (CEC) has an effect on erosion factor (M), Above 10 cmol/kg, CEC an increase in its value has very small effect on the erosion rate constant (Ariathurai et al., 1978). Also, critical stress has been found to increase with the clay content (CEC) up to a point and then stay constant. Sodium adsorption ratio (SAR) is low for all soils which produces interparticle attraction explaining flocculation which makes it easier for the particle to be eroded unless the bonding between them is strong. Here again the effect of increasing SAR is to reduce the value of M rapidly at first and then more gradually (Ariathurai et al., 1978). DTPA Micronutrients in the floodplain are high, due to deposition of eroded particles from upland. Organic matter estimated from the total C varied between 30.5 g/kg for bank soil to 74.2 g/kg for floodplain soil. Even 1-3% of organic matter can reduce erosion up to 20-33%, but organic matter is depreciated in the tilled soil where it is even lower i.e., Corn - 43.6 g/kg & Soybean – 54.9 g/kg. Plot studies at the Hilton experimental site, Shropshire (U.K.) show that small reductions in soil organic content markedly increase erodibility and erosion rates (Fullen M.A., 1991). Organic carbon in corn varies as its photosynthetic pathway (metabolism), which is C4. Corn soil and bank soil due to lower organic content are apparently less stable as SOM is the major binding agent observed. Similarly, for soybean NO_3-N is lower it is converted at a faster rate. CRP being Brome grass belongs to the C3 pathway which is seen in the results of organic matter/total C and NO_3-N, where both soils have closer values. The variability of fingerprint property concentrations for different sources should be included in mixing model calculations to enable the provision of confidence limits for the estimates of the relative contributions from each potential source (Collins et al., 1998). Though rates of mechanically caused erosion are large, it is chemical weathering that replaces exchangeable bases in acid soils of temporal regions receiving acidic deposition, the Base Exchange capacity of the soils would be completely vanished over a period of 50-100 years (Stumm, 1998).

5.2 Numerical Modeling

In this study, the sub-catchment of interest is simulated for three single storms within 2004-2005 (see Figure 1 & Table 2) and for 2 years (2004-2005) of continuous corn-soybean rotation period (see Figure 2). The 6/25/2005 event produces the highest erosion rates amongst all of the simulated events and is presented herein.

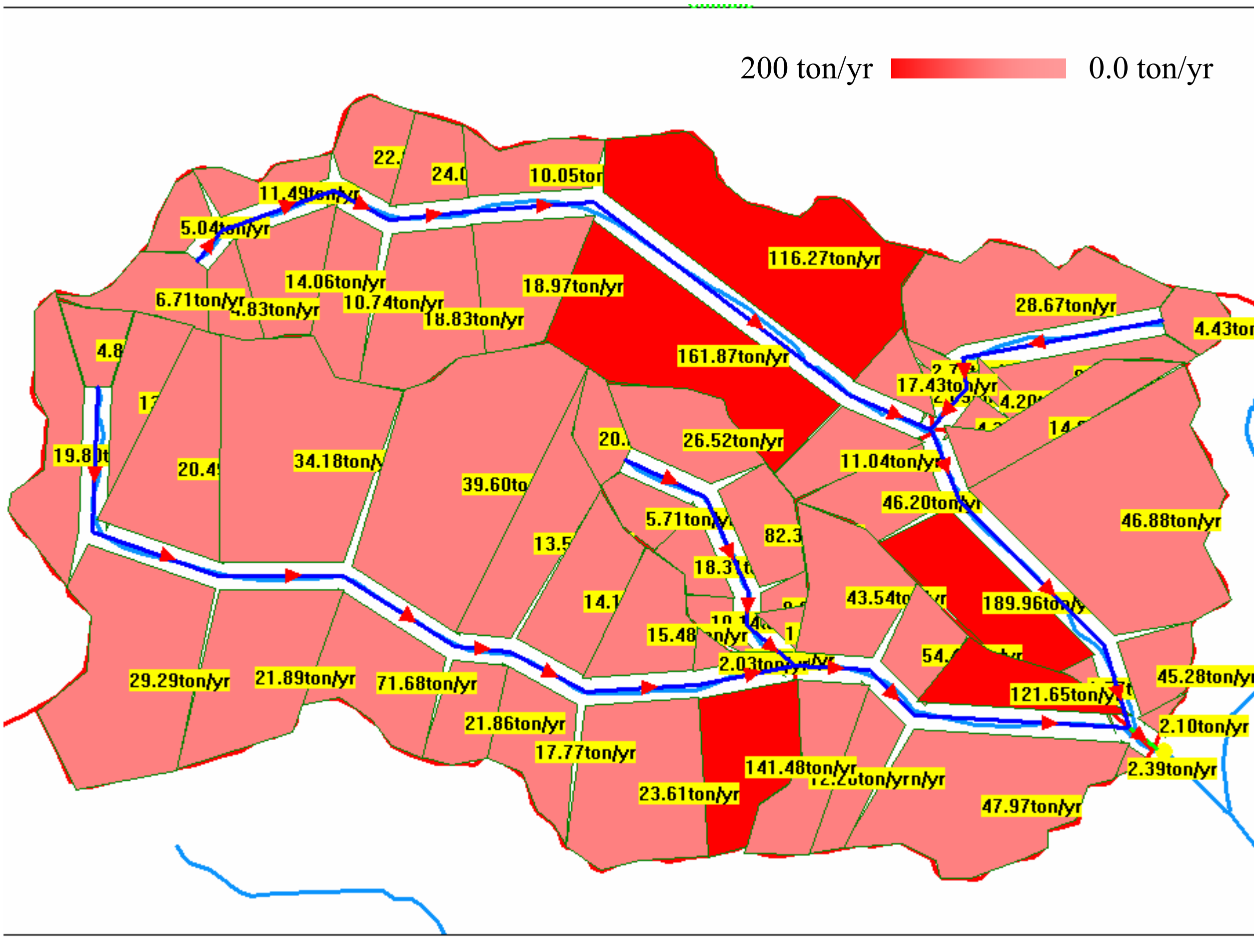

Figure 1 Sediment yield by hillslope for simulation of 6/25/2005 storm

Table 2 Strongest storms between 2004 and 2005.

Date	Storm Amount	Storm Duration	Maximum Intensity	% Peak Intensity
---	[in]	[hr]	[in/hr]	---
9/14/2004	2.45	5	1.59	35
6/20/2005	1.59	2	2.92	88
6/25/2005	2.78	3	2.28	25

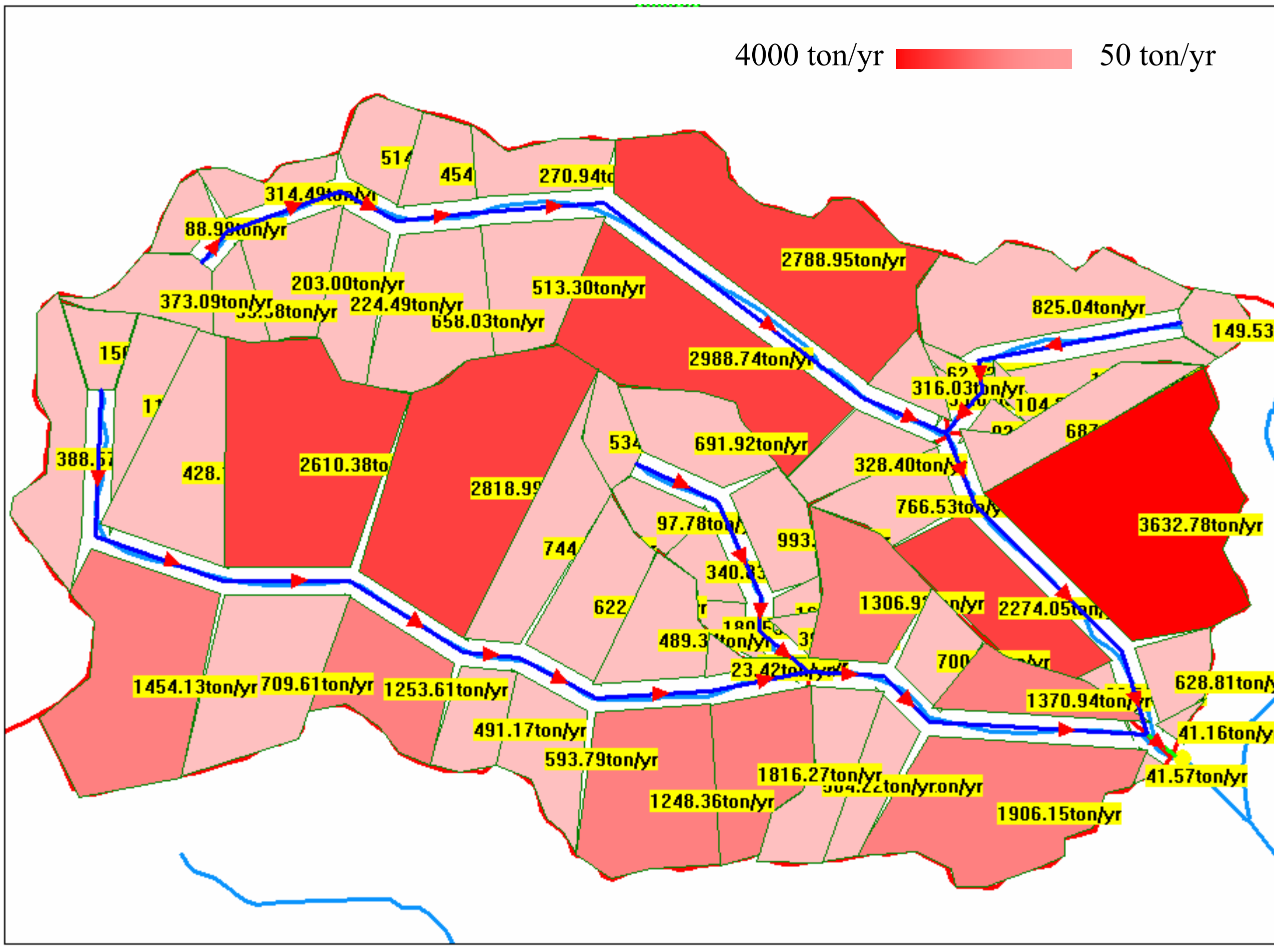

Figure 2 Sediment yield by hillslope for 2 years continuous simulation.

The watershed model consists of 62 hillslopes and 29 channels. In year 2004, 122 storms produced 805.17 mm of rainfall and 36 events produced 402.79 mm of runoff passing through the watershed outlet. In year 2005, 107 storms produced 864.57 mm of rainfall and 30 events produced 248.04 mm of runoff passing through the watershed outlet. On an average annual basis, 114 storms produced 834.87 mm of rainfall and 33 events produced 325.42 mm of runoff passing through the watershed outlet. As a result of simplistic single slope hillslope definitions, all of the eroded soil yielded and no deposition is observed within none of the hillslopes. WEPP calculated the sediment delivery ratio for the whole watershed as 0.577. As Figure 1 shows sediment yield by hillslope without contributing the hillslope areas, it would be more accurate to divide the sediment yield results by the hillslope areas so that the obtained erodibility measure will provide better comparison with the outcomes of the biogeochemical analysis. Overall, the whole watershed produced 4.9 tones/acre/year sediment yield. 26 hillslopes were prone to higher than 10 tones/acre/year soil loss. Table 2 presents the characteristics of strongest storms between years 2004 and 2005. % Peak Intensity is the time (in percent of the storm duration value) at which the peak intensity of the storm occurs. For example, if the peak intensity occurs at hour 8 of a 10-hour storm, then % peak Intensity would be 80 %. After running all three events in WEPP, the event of 6/25/2005 produced the highest erosion rates throughout the whole sub-catchment.

As can be seen in Figures 1 and 2, although the order of soil loss from the single storm simulation drops down to approximately 1/20th of the continuous simulation, the hillslopes that are prone to highest amounts of soil erosion mostly remain the same. Being aware of the magnitude of soil loss due to simulated single storm, it is important to repeat that a few intense storms are responsible for most of the annual erosion.

5. CONCLUSIONS

This work exhibits the utility of biogeochemical characteristics of source soil to understand erodibility and presents the results of a numerical upland erosion model. In this investigation we see that not only does consequent tilling of soils make soil susceptible, even the uncultivated soils get affected by deposition of the soil eroded from cultivated land. These are best represented by the biogeochemical characteristics viz., pH, CEC, SAR, organic matter and water content. pH values lie in the range of 6.0-7.0 or at the breakpoint for particles to undergo erosion. CEC of agricultural soils is an important characteristic in categorizing the soil, values nearing to 10mol/kg require further investigation as it directly affects the erosion factor. SAR was relatively low for all soils, calling for low shear to erode the particles. Organic matter being the binding agent has seen to be depreciating in different land uses, which nonetheless can be attributed to exposure during tilling, which negative criteria for stability of the soil. Also, these chemical test values accord with the geological results, wherein the water content is less for the uncovered soil, signifying the importance of vegetation cover in erosion reduction. Biological photosynthetic pathways for each crop solve the issue with the difference in the total C and NO_3-N. Thus, the advantage of doing biogeochemical characterization is the complete incorporation in magnitude of the variability associated with the source soil characteristics in the model sediment delivery estimation. Moreover, WEPP simulation indicates that the Upper South Amana sub-catchment, on average, is prone to 5 tones/acre/year soil loss. 26 hillslopes were prone to higher than 10 tones/acre/year soil loss. Highly erodible regions did not change in case of both continuous and single storm simulations. Single storm simulations verified the statement that a few intense storms cause most of the annual erosion. The event of 6/25/2005 produced the highest erosion rates throughout the whole sub-catchment.

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