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The Daily Erosion Project - High Resolution, Daily Estimates of Runoff, Detachment, Erosion, and Soil Moisture

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Abstract. Runoff and sediment transport from agricultural uplands are substantial threats to water quality and sustained crop production. Farmers, conservationists, and policy makers must understand how landforms, soil types, farming practices, and rainfall affect soil erosion and runoff in order to improve management of soil and water resources. A system was designed and implemented a decade ago to inventory precipitation, runoff, and soil erosion across the state of Iowa, United States. That system utilized the Water Erosion Prediction Project (WEPP) soil erosion model along with radar-derived precipitation data and government-provided slope, soil, and management information to produce daily estimates of soil erosion and runoff at the township scale (93 km2 [36 mi2]). This project has refined the original methodology by using remote sensing techniques and improved databases to accurately determine topography and the spatial distribution of cropping and soil management practices in Iowa. These enhanced parameters along with more detailed meteorological data are used as inputs to WEPP to estimate soil erosion and runoff daily at the hillslope scale. Results are averaged and reported at the scale of small watersheds with an average area of approximately 90 km2 (35 mi2). The revisions constitute a substantial improvement because actual field conditions are reflected, better weather data are utilized, hill slope sampling intensity is an order of magnitude greater, and results are grouped based on surface hydrology. Statistical and comparative evaluations of soil erosion simulations indicate that the sampling framework is adequate and the results are defendable. Various extensions of this work are also proposed.
Keywords. remote sensing—soil erosion—WEPP

Soil erosion by water poses one of the foremost environmental challenges in agricultural landscapes. Topsoil loss reduces agricultural productivity, and sediment delivery to downhill and downstream locations causes ecological and economic damages (Pimentel et al. 1995; Uri 2000). Soil stores and releases water and nutrients, so its capacity to do so has direct impacts on agricultural productivity and water quality (Hatfield et al. 2013). Thus, understanding soil degradation is critical from agronomic and environmental perspectives.

Soil erosion is an episodic process that depends on biophysical and human factors. Rainfall and runoff are the primary drivers of soil erosion in humid regions. Because precipitation patterns exhibit large spatiotemporal variability, soil erosion rates are also highly variable in space and time. Rainfall and water runoff exert erosive forces on soil, but the degree to which soil is eroded is also highly dependent upon natural conditions; such as, topography, soil properties, and anthropogenic factors including agricultural management and conservation practices (Browning et al. 1947). The interactions between rainfall and underlying biophysical parameters are complex. Soil erosion models can be used to estimate the magnitude of soil erosion that results from these interactions.

Measuring soil erosion across a large geopolitical region (e.g., Iowa, United States, with an area of 145,743 km^2 [56,272 mi^2]) is a resource-intensive proposition. Along with an appropriate analytical framework and reliable input data, a soil erosion model can be used to attain similar results without investment in field- or basin-scale monitoring. Model output could then be evaluated to prioritize sub-regions that would benefit from conservation planning for soil and water resources. Such assessments will become increasingly necessary due to growing awareness of the environmental impacts of agriculture and due to the unknown effects of future land use and climate conditions.

In fact, precipitation in the north central United States is increasing in amount, frequency, and intensity (Karl and Knight 1998; Todd et al. 2006) and this region is experiencing heavy rainfall events more often (Villarini et al. 2013). Such extreme individual events are increasing in magnitude, and this trend is projected to continue (SWCS 2003; Pryor et al. 2014), further exacerbating the problem that most soil erosion occurs during infrequent heavy rain events (Larson et al. 1997). Amplifying this concern, soil erosion is estimated to increase by a factor of 1.7 compared to rainfall intensity increase (Nearing et al., 2004). Understanding the impact of individual rainstorms on soil erosion is critical, and a regional modeling approach can yield important insights.

Such a project was developed and implemented for the state of Iowa by Cruse et al. (2006). The program used soils, topography, and crop management information obtained from the USDA-Natural Resources Conservation Service (NRCS) National Resources Inventory (NRI) (Nusser and Goebel 1997) along with NEXt-Generation Weather RADar (NEXRAD) rainfall data and Iowa Environmental Mesonet meteorological information as inputs to a soil erosion model to generate daily estimates of average precipitation, runoff, soil moisture, and soil erosion at the township scale (93 km^2 [36 mi^2]) across Iowa (Cruse et al. 2006). Daily simulations were run for 17,848 confidential agricultural hillslope locations within Iowa (Cruse et al. 2006).

Statewide observation of the biophysical factors influencing erosion allows for the generation of a database of soil erosion model inputs that accurately reflect actual environmental and management conditions. Advances in remote sensing have created opportunities to obtain high-resolution geospatial data with respect to topography and enabled near real time tillage practice estimates in particular. Along with updated soils and land use databases, a more accurate picture of the factors influencing soil erosion can be drawn. The goal of this project, the Daily Erosion Project (DEP), is to improve upon the prototype system of Cruse et al. (2006) by leveraging real-time remotely sensed and spatially distributed inputs to model soil erosion and runoff at the hillslope scale. The objectives of this paper are to: 1) describe a modeling and database input structure supportive of remotely sensed inputs and reporting at the small watershed resolution; 2) test stability of soil erosion estimates based on hill slope sampling protocol; and 3) compare DEP estimated sheet and rill soil erosion values to NRI statewide erosion estimates within the period encompassed by existing DEP data bases.

Materials and Methods

The four major DEP components are the soil erosion model (WEPP); the soil, topography, and land management input database; daily weather information; and a sampling and scaling approach for the daily modeling and reporting, respectively, of hillslope soil erosion and water runoff in Iowa. Substantial revisions from the first version (Cruse et al. 2006) include complex (versus uniform) hillslope modeling, annually updated remotely sensed soil management and land use databases (rather than NRI-supplied information), and hydrological (rather than geopolitical) discretization of the state for analysis and reporting. Outputs reported for each HUC 12 include average daily precipitation, average soil detachment per hillslope and average deliver of detached sediment to the base of the modeled hillslope.

Water Erosion Prediction Project. The Water Erosion Prediction Project (WEPP) hillslope model (Flanagan and Nearing 1995) was selected for the DEP. WEPP simulates rill and interrill erosion by rainfall and runoff and spatiotemporal distributions of soil detachment and sediment delivery (Flanagan and Nearing 1995). The basic element on which WEPP is implemented is a hillslope, which consists of one or more overland flow elements (OFEs). An OFE is a hillslope segment that represents a unique combination of slope, soil type, and land use.

Studies have validated the accuracy and unbiasedness of WEPP erosion estimates and confirmed its applicability in a broad range of conditions (Tiwari et al. 2000; Laflen et al. 2004). Motivations to select WEPP for this project include its capability to run continuous daily simulations and for modeling runoff and erosion on complex hillslopes. The DEP executes WEPP as a continuous simulation model to generate daily estimates of runoff, soil erosion, and soil moisture across Iowa. The WEPP model simulation is supplied daily meteorological data, and the field specific crop and soil management parameters needed to run the model are assembled in an annually updated database.

Input database. In addition to weather, the required WEPP inputs are topography, soils, and agricultural land management. In the original implementation of this project, slope, soil, and cropping and conservation practice information were obtained from the NRI (Cruse et al. 2006). While the NRI sampling points are based on actual locations (Nusser and Goebel 1997), the precise locations cannot be disclosed due to privacy concerns and potential operator bias (Cruse et al. 2006). Thus, in an effort to realistically assess soil erosion on a spatially explicit and daily time scale, a new database of WEPP inputs has been developed. The three primary biophysical conditions that are inventoried for the DEP are topography, soils, and management.

Assumed uniform slopes were the only topographic product available in the first iteration of this project (Cruse et al. 2006). However, actual hillslopes are typically complex. In terms of erosion modeling, complex slopes can result in greatly different output relative to uniform slopes because complex hillslopes often experience varying levels of erosion and/or deposition at different points along the slope. For the DEP, high-resolution topographic data are used to construct discrete hillslopes for modeling erosion. Light Detection and Ranging (LiDAR) data, available from the Iowa Department of Natural Resources, were processed with custom algorithms to generate a 3 m (9.8 ft) digital elevation model (DEM) of each HUC12 (USDA-NRCS, USGS, USEPA, 2012) watershed in Iowa. Details of the hydrologic enforcement process can be found in Gelder (2015). Processing settings maintain all depressions deeper than 9 cm (0.5xRMSE) or larger than 100 square meters.

Soil information is obtained from the gridded Soil Survey Geographic Database (gSSURGO) (Soil Survey Staff, 2014). Geospatial soil data are registered with the DEM for each HUC12 watershed.

The final component of the WEPP input database is management, which is separated into crop rotation (or sequences) and tillage practice for each agricultural field in the state greater than 6 ha. Crop rotations are determined for each field using the USDA-National Agricultural Statistics Service (NASS) Cropland Data Layer (USDA, 2014). A six-year rotation is derived from each field's most recent crop history and is used to preprocess the WEPP model to condition crop growth and antecedent soil moisture conditions at model initiation. The land use for the model (current) year within each field is based on the field's six year rotation, extending that rotation one additional year considering the preceding year's crop. Land use data are updated annually (Tomer, 2015). Tillage practices are estimated for each field using Landsat 8 imagery. From the normalized difference tillage index (NDTI) the amount of residue cover on the soil surface is empirically derived (Gelder et al., 2009), which is then correlated to one of four tillage intensity classes which correspond to typical conventional tillage, intensive mulch tillage, reduced mulch tillage, and no-tillage practices.

After determination of crop rotation and tillage practice for each agricultural land parcel, these parcels are rasterized along with the elevation and soils data. This geo-referenced ensemble of topographic, soil, and land management information is used to extract data to populate WEPP OFE and hillslope input files.

Meteorological data. The WEPP model requires the following meteorological data: daily high and low temperature, solar radiation, average wind speed, average dew point temperature, and precipitation. All of these variables, except precipitation, are derived from weather observations collected and analyzed by the Iowa Environmental Mesonet. These observations are gridded onto a 0.01 by 0.01 degree resolution grid. For precipitation, gridded estimates are provided by the NOAA Multi-RADAR Multi-Sensor (MRMS) RADAR-Only "Q3" product. This product provides a 0.01 degree resolution precipitation analysis at a two minute temporal resolution which is resampled to a 1.0 by 1.0 kilometer, five minute temporal resolution product for use in the DEP.

Sampling framework. Daily soil erosion and runoff are simulated for individual hillslopes, but results are averaged across all modeled hillslopes within a given HUC12 and reported at the HUC12 watershed level. Thus, a procedure was developed to select hillslopes for soil erosion and water runoff estimates and to transform the scale of the model output to that of the HUC12 watershed. The primary goal of the sampling approach was to generate statistically robust average runoff and erosion estimates for each HUC12 watershed in Iowa.

The average Iowa HUC 12 area is approximately 90 km^2 (35 mi^2), comparable to the area of a township (93 km^2 [36 mi^2]). A stratified random sampling approach was developed to insure hillslopes were selected randomly while being distributed across each HUC12. Each HUC12 watershed is separated into hydrologically-determined sub-catchments, which serve as the stratified sampling structure, by using two TauDEM (Tarboton, 2014) methods; the Peuker Douglas stream definition method that employs a constant drop approach (Tarboton and Ames, 2001), and the subsequent Stream Reach and Watershed method to establish sub-catchments.

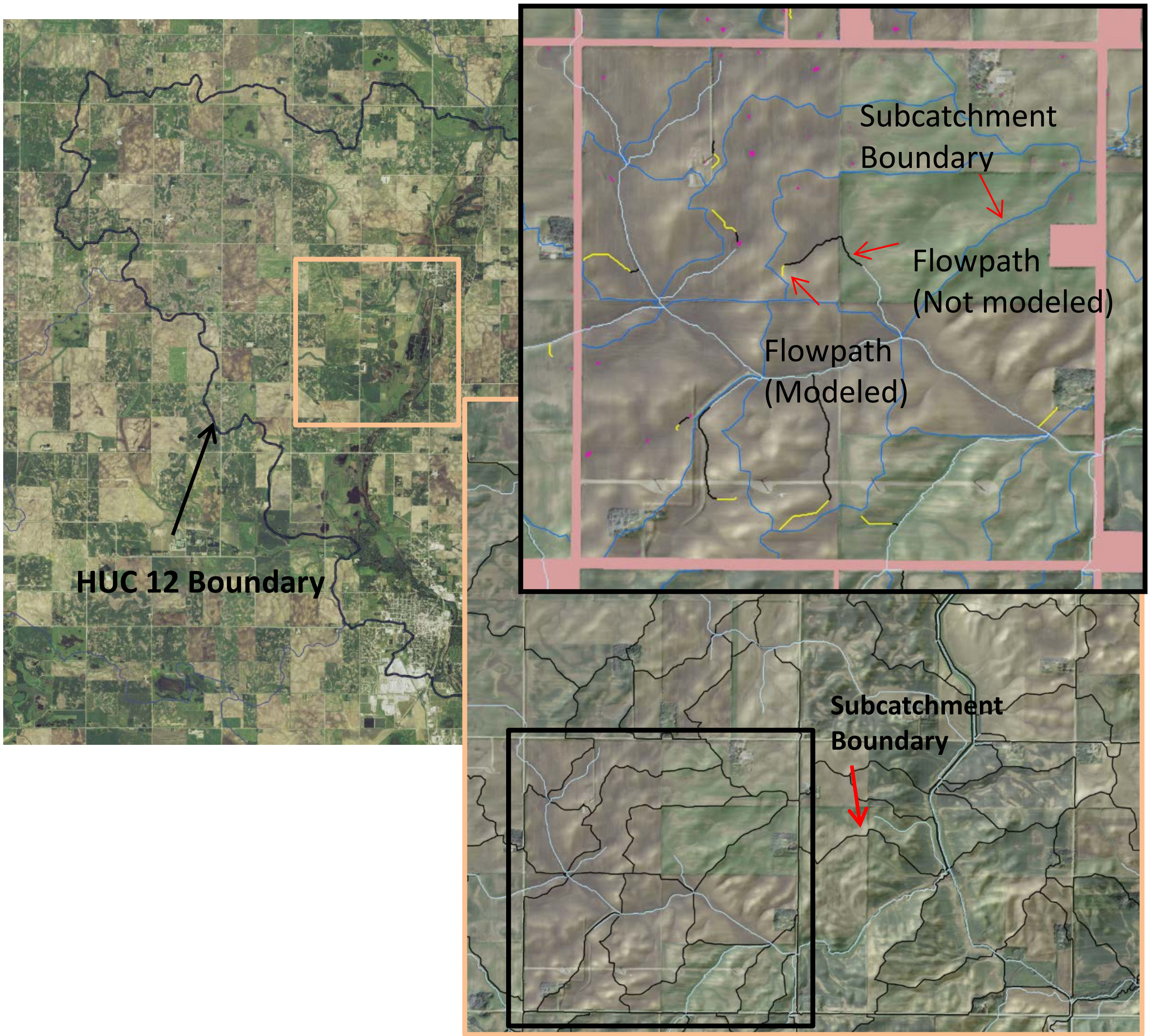

Figure 1. Diagram of HUC 12 Boundary (left), Subcatchment Boundary (lower right inset), and Modeled and Non-modeled Flowpath Elements (upper right inset)

The goal of this process is to derive between 100-200 sub-catchments per HUC12 watershed. The final number of sub-catchments depends on the size and shape of the watershed and on agricultural density requirements. Initially, at least 75 percent of the sub-catchment must be in agricultural land use to be a candidate sampling location. The 75-percentile threshold is adjusted iteratively in order to achieve the desired number of candidate sub-catchments within each HUC 12.

Within each sub-catchment one randomly selected flowpath is identified. For a given sub-catchment, each grid cell in the DEM is assigned to a flow accumulation class. All grid cells with a flow accumulation of zero (FA0) are the domain of potential flowpath initiation points. One FA0 cell within the sub-catchment is randomly selected, and the DEM is used to determine the subsequent cells into which water would flow. Flowpaths terminate when non-agricultural land uses are encountered or when flow is interrupted by physiographic features, such as, road ditches, agricultural terraces, or potholes. Additionally, flowpaths are truncated when collective flow dominates the flowpath. Collective flow is modeled using a Strahler grid order raster where;

> “Strahler order is defined as follows: A network of flow paths is defined by the D8 Flow Direction grid. Source flow paths have a Strahler order number of one. When two flow paths of different order join, the order of the downstream flow path is the order of the highest incoming flow path. When two flow paths of equal order join, the downstream flow path order is increased by 1.” (Tarboton, 2014)

DEP flowpaths are arbitrarily truncated where the Strahler grid order becomes greater than 4. Truncation limits inclusion of excessively long flowpaths or modeling of landscape areas that may experience soil erosion processes for which the WEPP hillslope model should not be applied due to substantial runoff concentration (i.e., ephemeral or classical gully erosion). The cells included in the flowpath are then exported to a flowpath raster. This flowpath raster is then registered to the geospatial database of topographic, soils, and management information. The slope, soil, and management data corresponding to each grid cell in a flowpath raster are extracted and written to a file for WEPP input. Each unique combination of soil and management result in a WEPP Overland Flow Element (OFE) and slope is calculated for each OFE.

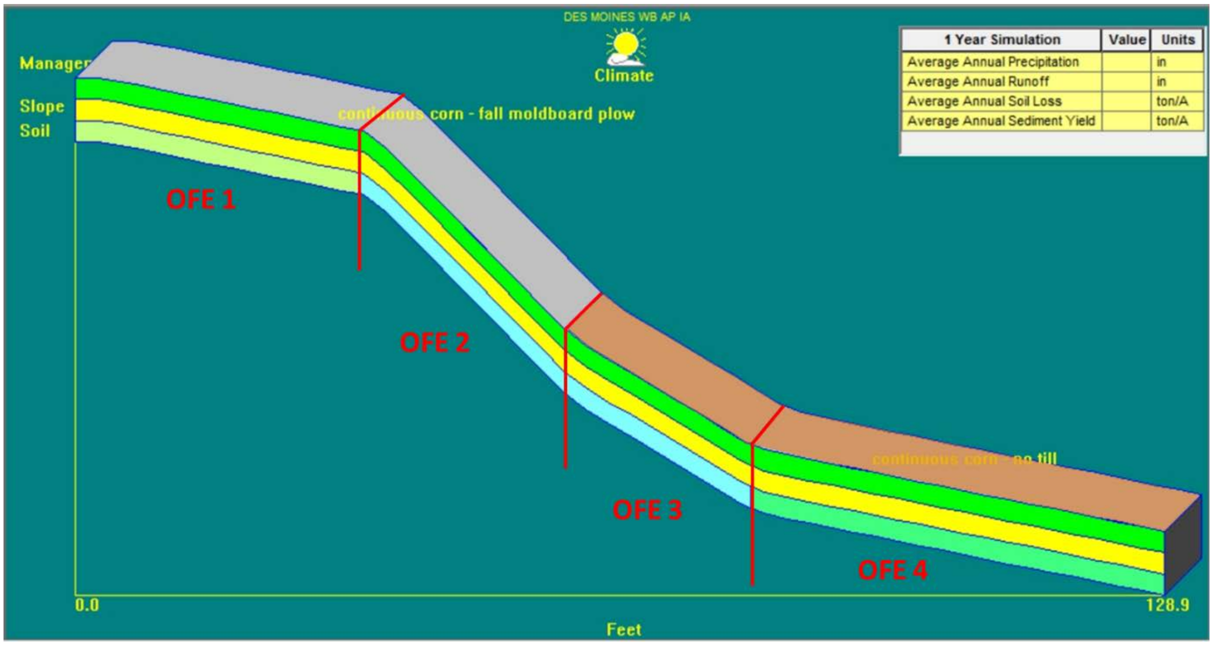

Figure 2 Example WEPP Overland Flow Element (OFE) diagram showing three unique soils and two unique managements.

Approximately 202,000 flowpaths in Iowa have been generated and are modeled for this project. After each daily WEPP simulation is complete, the output values for all flowpaths within a HUC12 watershed are averaged. These average values are then spatially related to a map of Iowa HUC12 watersheds that is accessible on the Internet at http://dailyerosion.org.

Statewide simulation. DEP soil erosion estimates were compared to the National Resources Inventory (NRI) statewide soil erosion estimates to test appropriateness of DEP estimates.

Evaluation of soil erosion simulations. Estimated soil erosion rates, sediment delivery to the modeled flowpath termination point, were assessed in two ways. First, 2007 to 2014 statewide average total soil erosion estimates were compared to NRI values from 2007 and 2012 (U.S. Department of Agriculture. 2015). Second, the statistical validity of sampling 1 flowpath per sub-catchment was tested by comparing HUC12 watershed average annual soil erosion values against average annual estimates using up to 10 generated and modeled flowpaths for each sub-catchment in a given HUC12 watershed. Three HUC12 watersheds were randomly selected from each of the 10 major land resource areas (MLRAs) in Iowa, for a total of 30. For 2007 to 2014 the total annual soil erosion was simulated in each of the 30 HUC12 watersheds using 1 to 10 flowpaths per sub-catchment. Two-sample *t*-tests were conducted for each year to test the null hypothesis that the mean estimated soil erosion rate does not change if the number of flowpaths used to calculate average values for the 30 HUC12 watersheds is increased.

Results and Discussion

Daily estimated soil erosion rates varied substantially depending especially on spatial and temporal distribution of rainfall as it interacts with topography.

Precipitation output

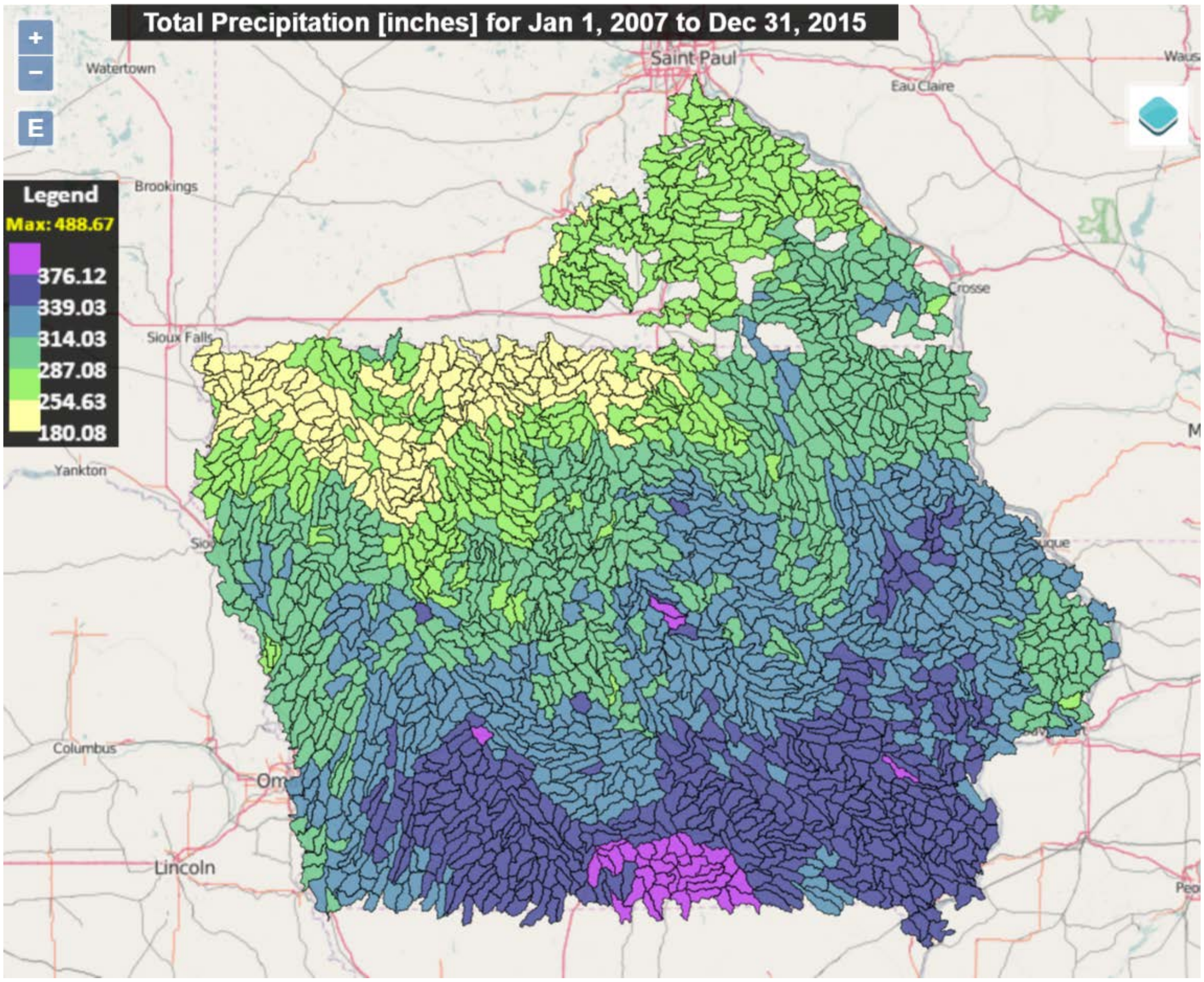

Figure 3. Total Precipitation from 2007 through 2015 by HUC12 Watershed for current domain excluding Kansas

Runoff and soil erosion output

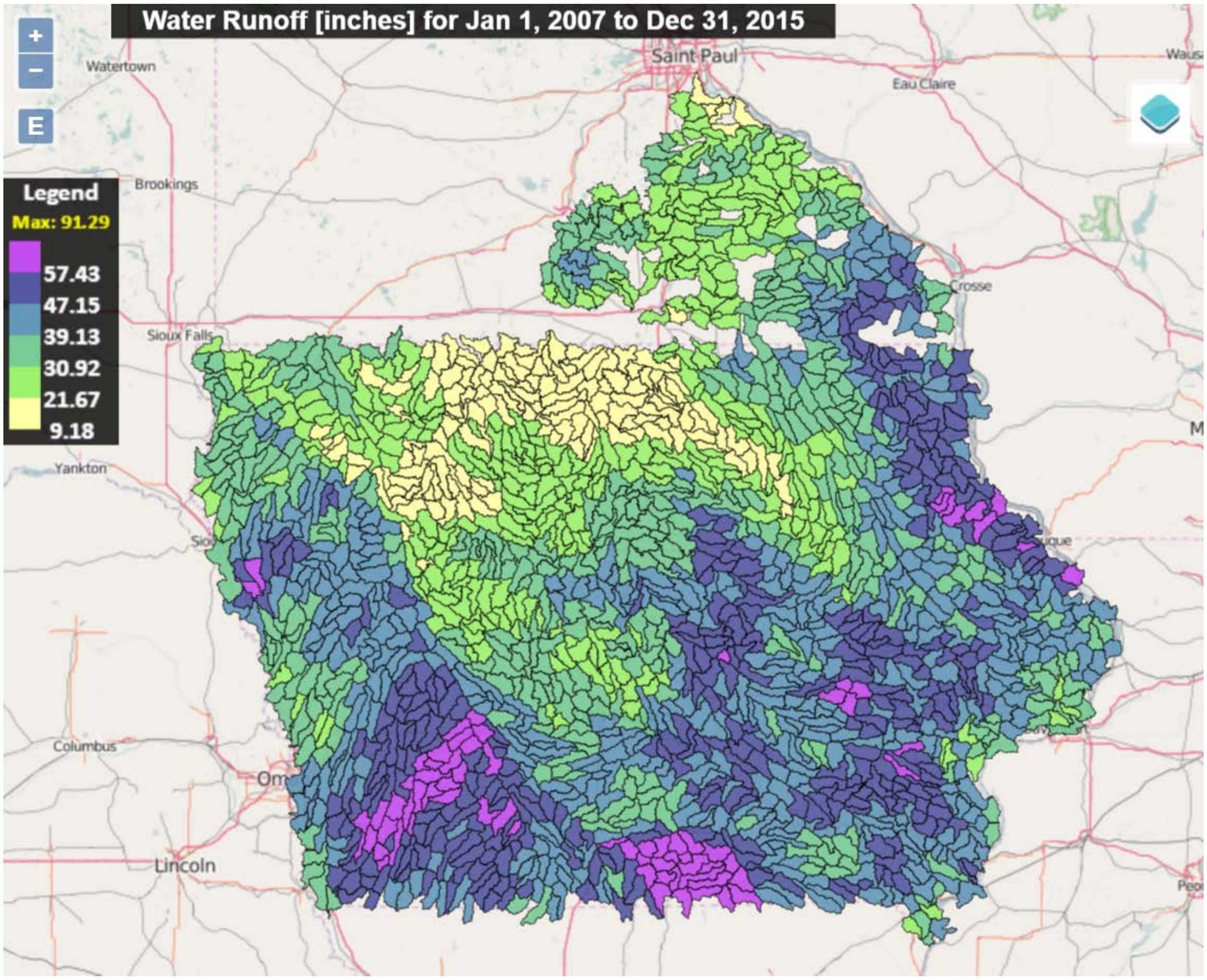

Figure 4. Total Runoff from 2007 through 2015 by HUC12 Watershed for current domain excluding Kansas

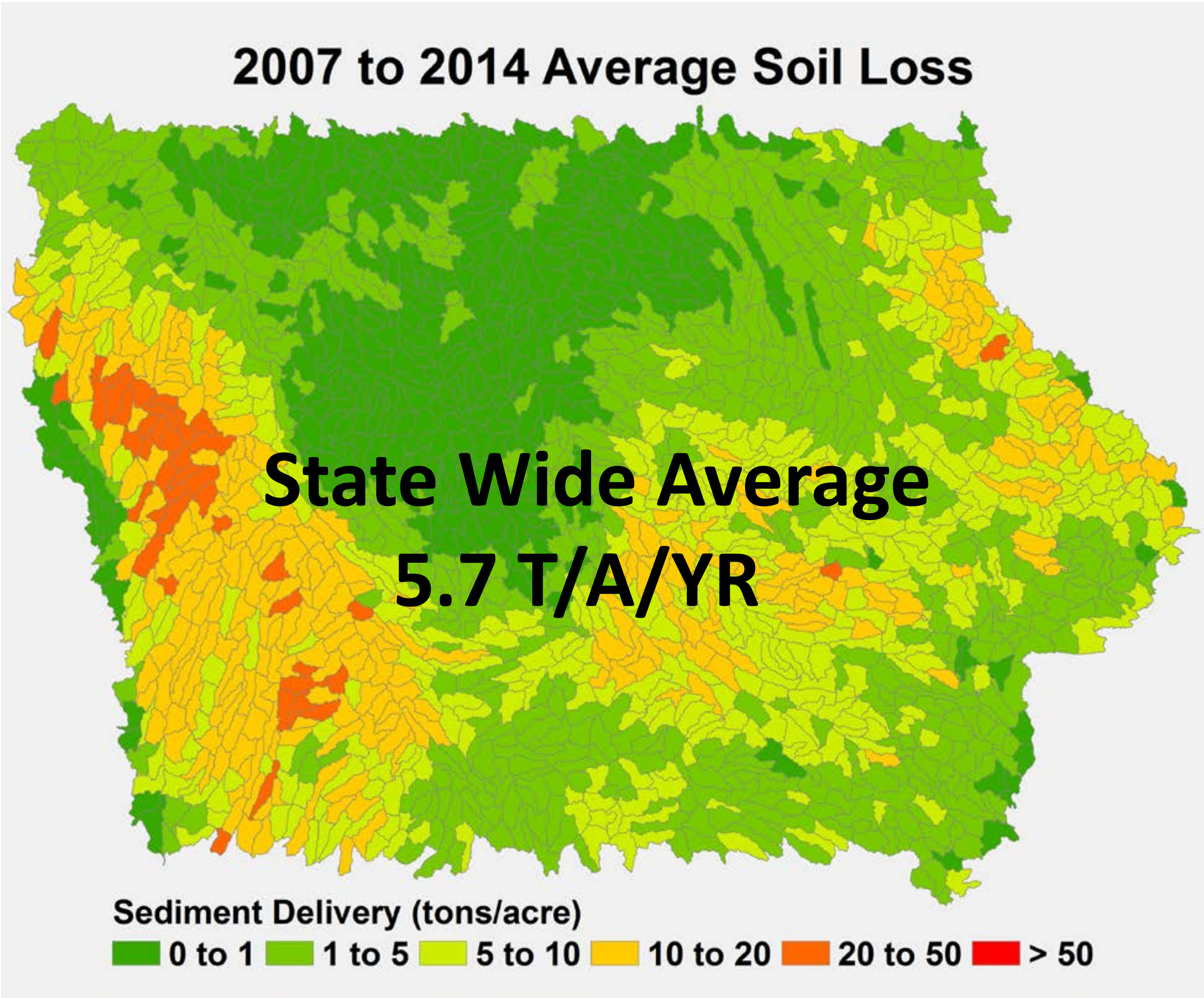

Figure 5. Iowa HUC12 Average Erosion Rates from 2007 to 2014

Limitations and opportunities. It bears repeating that the DEP does not estimate gully or concentrated flow erosion or delivery to a river or stream. This approach is currently being expanded to other neighboring states and has potential for evaluating future climate and/or LU/LC scenarios. We are working to validate model output with monitoring data and also looking to predict Phosphorus movement and management impacts on flood volumes.

Summary and Conclusions

The DEP graphically illustrates the factors dominating soil erosion such as topography, rainfall, and cropping practices. Iowa is dominated by corn and soybeans crop cover and this strongly influences erosion rates as corn produces large amounts of biomass and soybean relatively little but both crops leave the ground uncovered for over half the year, especially in the spring when higher rainfall intensity and volume is likely. The results, when standardized by precipitation or management, can thus be used to identify highest-risk areas and prioritize conservation practice implementation. They can also be used to estimate gross yield losses due to long term erosion impacts.

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