DEVELOPMENT AND APPLICATION OF GULLY EROSION COMPONENTS WITHIN THE USDA ANNAGNPS WATERSHED MODEL FOR PRECISION CONSERVATION

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ABSTRACT

A watershed scale assessment of the effect of conservation practices on the environment is critical when recommending conservation management practices to agricultural producers. The identification of all sources of sediment and subsequent tracking of the movement of sediment downstream is a necessary part of this assessment including the often overlooked contributions from gully erosion sources. Pollutant loading allocations established with comprehensive studies of all sediment sources will result in the precise placement of conservation practices to those locations that will have the most effective impact on reducing watershed sediment loads. The USDA Annualized Agricultural Nonpoint Source model (AnnAGNPS) was developed to perform watershed evaluations of conservation management plans that can be implemented to control all sources of sediment, including from gullies, and is a critical tool in watershed project planning. These enhancements include the development of ephemeral and classic gully components within AnnAGNPS and within geographic information system interface tools used to locate and parameterize gully information for use in the model. Many agricultural conservation practices have been implemented that impact gully erosion, such as conservation tillage, agricultural land conversion to CRP land, grassed waterways, and drop pipes, but there has not been an effective tool developed that can be used to evaluate these practices on controlling gully erosion within watershed systems. An analysis was performed within selected watersheds to demonstrate the applicability of utilizing AnnAGNPS to assess the contribution of gully erosion to a watershed's total sediment load and the effectiveness of conservation practices designed to control gully erosion. Watershed model studies can provide critical information in a timely manner to action agencies, such as the USDA Natural Resources Conservation Service, when planning where to place effective conservation practices within a watershed.

Keywords: **Ephemeral Gullies, Erosion, Sediment, Watershed Models.**

INTRODUCTION

Assessment of the effectiveness of conservation practices within agricultural watersheds is critical when planning the best options to control erosion and where they should be applied. The identification of all sources of sediment and subsequent tracking of the movement of sediment downstream is a necessary part of this assessment including the often overlooked contributions from gully erosion sources. Many agricultural conservation practices have been implemented that impact not only sheet and rill erosion, but gully erosion, such as conservation tillage, agricultural land conversion to CRP land, grassed waterways, and drop pipes, but there has not been an effective tool developed that can be used to evaluate these practices on controlling gully erosion within watershed systems. As a result, there is limited technology available to evaluate gully erosion control practices.

USDA-Natural Resource Conservation Service (NRCS) has been the authority on erosion prediction and control since the Dust Bowl days of the 1930's in the U.S. NRCS currently focuses primarily on sheet and rill erosion to set conservation planning goals and for measuring, predicting, assessing, and reporting water erosion control. Many studies have shown that ephemeral gully formation is very common on cropland, especially in conventional tillage systems without support practices (Gordon et al., 2008). Ephemeral gully erosion is believed to be as significant as sheet and rill erosion in terms of sediment delivered from cropland acres to streams, rivers, and lakes. Some studies have found that ephemeral gully erosion contributes about 40% of the watershed sediment yield (Gordon et al., 2007). Sediment delivery from farm fields from all erosion sources is also much higher when ephemeral gullies are present since gullies provide pathways for sediment transport to the downstream channel system. Research on the extent of contributions from all erosion sources to in-stream sediment loads is sparse. Few models account for and specifically predict ephemeral gully erosion. Although the National Resources Inventory (NRI) reports an estimated 42% reduction in sheet and rill erosion over the past 20 years, sediment loads in major rivers remain at high levels, prompting the U.S. Environmental Protection Agency (USEPA) to continue to rank sediment as the predominant cause of non-point source pollution in the country. The reason for this is because not all sources of sediment are being controlled and accounted for, including concentrated flow sources and especially ephemeral gully erosion.

The amount of soil saved as a result of applying conservation practices to control ephemeral gully erosion has not been measured and NRCS does not have a tool to predict and quantify ephemeral gully erosion, including the potential for nonstructural practices to control the erosion. Unlike sheet and rill erosion, which occurs as a result of the impact of raindrops and water flowing on the soil surface, ephemeral gully erosion occurs as a result of concentrated flow of surface runoff along a defined channel, and also by subsurface flow by seepage and flow through preferential pathways. Erosion in these channels is not predicted by RUSLE

(Revised Universal Soil Loss Equation) (Renard et al, 1997), and therefore is not accounted for in current soil loss assessments. A systematic method is needed to determine the extent of the ephemeral and all forms of gully erosion problems on a field, watershed, or national basis, and to predict the recurring or new locations of gullies prior to their development. This paper will describe technology developed to account for all sources of sediment including gullies. Applications of this technology used to evaluate the effectiveness of conservation practices and their most efficient placement within a watershed to control erosion is described to illustrate the capabilities and limitations for utilization of watershed modeling technology in watershed planning.

WATERSHED MODELING TECHNOLOGY

As a result of requests by NRCS to improve USDA-Agriculture Research Service (ARS) technology to account for watershed sources of sediment from gullies, the USDA AGricultural Non-Point Source pollution model (AGNPS, Bingner and Theurer, 2001a) was enhanced for NRCS watershed planning use. AGNPS is a joint ARS and NRCS suite of computer models developed to predict nonpoint source pollutant loadings within agricultural watersheds. The continuous-simulation, surface-runoff computer model called Annualized AGricultural Non-Point Source Pollution Model v5.0 (AnnAGNPS, Bingner and Theurer, 2001b) is the main component of this suite. AnnAGNPS is designed to assist with determining BMPs, the setting of Total Maximum Daily Loads (TMDLs), and for risk and cost/benefit analyses. The set of computer programs consist of: (1) input generation and editing as well as associated databases; (2) the "annualized" science and technology pollutant loading model for agricultural-related watersheds (AnnAGNPS); (3) output reformatting and analysis; and (4) the integration of more comprehensive routines–National Center for Computational Hydroscience and Engineering 1-Dimensional (CCHE1D) for the stream network processes; and (5) a stream corridor CONservational Channel Evaluation and Pollutant Transport System model (CONCEPTS). Not all of these models are integrated electronically together, but the use of AnnAGNPS can produce common input/output that, with the use of standard text editors, can be linked.

The input programs include: (1) a GIS-assisted computer program (TOpographic PArameteriZation (TOPAZ) with an interface to AGNPS) to develop terrain-following cells with all the needed hydrologic and hydraulic parameters that can be calculated from readily available DEM's; and (2) an input editor to initialize, complete, and/or revise the input data. AnnAGNPS includes up-to-date technology–e.g., RUSLE and pesticides–as well as the daily features necessary for continuous simulation in a watershed. Additional features of AnnAGNPS include:

1. Water and sediment erosion, yield, and load by particle size class and source are calculated and determined to any point in the watershed channel system.
2. Gully components describing classical and ephemeral gullies within a watershed.

3. The capability to produce output related to soluble and attached nutrients (nitrogen, phosphorus, and organic carbon) and any number of pesticides.
4. A field pond water and sediment loading routine is included for rice/crawfish ponds that can be rotated with other land uses.
5. Nutrient concentrations from feedlots and other point sources are modeled. Individual feedlot potential ratings can also be derived using the model.
6. The applications of CCHE1D for stream networks and CONCEPTS for stream corridors include more detailed science for the channel hydraulics, morphology, and transport of sediments and contaminants.

AnnAGNPS is a continuous-simulation, mixed-land use, watershed-scale computer model designed to predict the origin and movement of water, sediment, and chemicals at any location in primarily agricultural watersheds. The model distinguishes between erosion caused by sheet and rill (from RUSLE version 1.06), tillage-induced ephemeral gullies (TIEG), other gully processes, and streambed and bank sources. Results from AnnAGNPS can be used to determine the amount of each pollutant (sediment and chemical loads) at any location in the watershed; i.e., how much of each pollutant comes from where and arrives at any location in the watershed. TIEGEM (Tillage-Induced Ephemeral Gully Erosion Model) is a new addition to AnnAGNPS that incorporates recent ARS research and is based on technology described by Bingner et al. (2007). Several algorithms are used within TIEGEM to determine the minimum gully width for each event: (1) previously determined width by a prior event; (2) Nachtergaele et al.'s (2002) equation 10; (3) the hydraulic geometry relationship for the gully's concentrated flow; (4) non-submerging tailwater depth at the crest of the headcut; (5) Woodward's (1999) equilibrium gully width; and (6) Woodward's (1999) ultimate gully width. Erosion from gullies is estimated using procedures describing the depth, width, and migration rate of the headcut (Alonso et al., 2002). Sediment delivered to the edge of fields and to the mouth of gullies is estimated using the HUSLE procedure (Hydro-geomorphic Universal Soil Loss Equation) (Theurer and Clarke, 1991).

Features within AnnAGNPS can be used to determine the probability and amount of a pollutant reaching any location within the watershed, including tillage-induced ephemeral gullies. To utilize the tillage-induced ephemeral gully feature in an AnnAGNPS analysis requires locating the mouth of each potential TIEG. Preliminary studies have been performed to identify the mouth of a gully headcut based on topographic analysis and have been integrated into AGNPS GIS user interface components (Parker et al., 2007).

Classic gully erosion is simulated through user-defined exponential functions of erosion based on the runoff flowing through the gully. The gullies can be located in any field throughout a watershed, but the coefficients and exponents of the function are user provided parameters requiring the user to have some prior knowledge of the erodibility of each gully. Improvements are needed to provide an enhanced process-based approach in estimating classic or edge-of-field gullies.

AnnAGNPS is currently available to quantify the magnitude and extent of tillage-induced ephemeral and classic gully erosion, sediment yield, and sediment load in watersheds from the AGNPS website (http://www.ars.usda.gov/Research/docs.htm?docid=5199). The results from the various sources could be correlated through land use, soils, and climate to indicate the magnitude and risk associated with pollutants originating from gullies.

An analysis will be performed within selected watersheds to demonstrate the applicability of utilizing AnnAGNPS to assess the contribution of gully erosion to a watershed's total sediment load and the effectiveness of conservation practices designed to control gully erosion. Watershed model studies can provide critical information in a timely manner to action agencies, such as the USDA Natural Resources Conservation Service (NRCS), when planning where to place effective conservation practices within a watershed.

GULLY DESCRIPTION

Gullies are dynamic erosion features within watershed landscapes. They are controlled by different processes such as climatic characteristics, topography, soil properties, vegetation cover, and land management. Soil properties and topography are often considered time independent due to the small temporal variation; while vegetation cover and land management vary over time as operations are performed that can influence runoff and erosion during different periods of the year. Capturing this dynamic behavior at the field level is important since variations from field management activities (crop and conservation practices) influence how gullies form.

This concept is illustrated on Figure 1 as the gully is being formed over the years. Initially, farming operations are carried out by plowing over the gully channel (2003). As the headcut of the gully moves upstream and becomes wider, the producer typically will operate their equipment around the gully channel. As the gully migrates upstream there is less drainage entering the upstream end of the gully resulting in less water to erode the channel and then less erosion from the slowing of the migration of the gully.

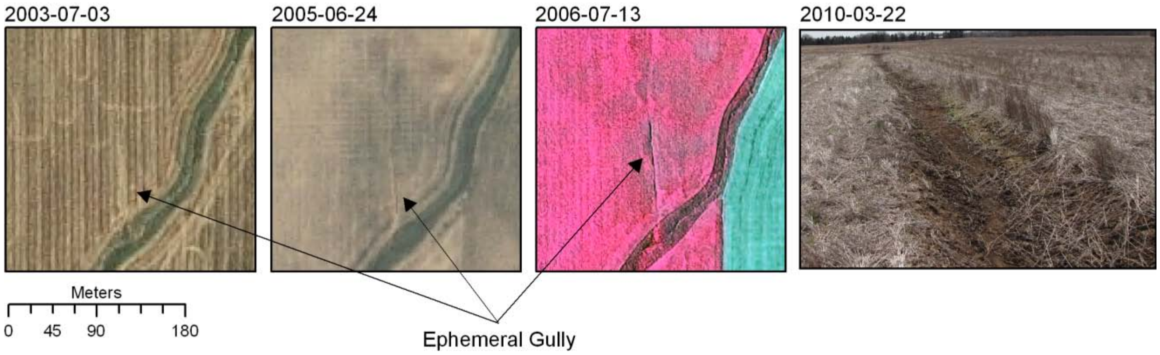

Figure 1. Illustration shows ephemeral gully evolution over time and disruption to producer's operations. Imagery data obtained from the National Agriculture Imagery Program (NAIP).

REMOTE SENSING TECHNOLOGY CHARACTERIZING GULLY LOCATIONS

Remote sensing can offer additional information for modeling/simulation of surface erosion processes. This technology can provide data over large regions, with a pre-determined sample interval (spatial resolution), without interfering with farming operations, and recording additional parts of the electromagnetic spectrum.

Utilization of distinct electromagnetic spectrum responses for different land-cover types can greatly enhance regional and local erosion investigations. Vegetation indices, such as the normalized difference vegetation index (NDVI), explores the differences in electromagnetic response between near infrared and red parts of the electromagnetic spectrum that remote sensing sensors record. For healthy green vegetation, reflectance values in the near infrared region are high and in the red region are low, yielding high NDVI values. Conversely, for bare/idle soil, reflectance in the infrared and red regions has similar values causing lower NDVI values. Equation 1 illustrates the concept.

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \quad [1]$$

Figure 2 shows an NDVI image of two adjacent fields. The high values indicate the presence of healthy green vegetation (field on the left) while the low values indicate exposed soil (field on the right).

Vegetation indices can provide estimates of green fraction vegetation cover. Rundquist (2002) described the direct linear relationship between squared scaled NDVI and green fraction vegetation cover. Combining multi-temporal remotely sensed estimates of fractional vegetation cover of individual fields with precipitation data and topography can lead to a ranking schema of fields for potential occurrence of ephemeral gullies. Figure 3 is a graph of multi-date values of estimated fraction vegetation cover obtained using MODIS vegetation indices product (MOD13Q1). NDVI values of the 16-day composite image were scaled using minimum and maximum NDVI values suggested by Rundquist (2002). The plot depicts differences in green vegetation cover between the two fields during the rain events in July, August, and September of 2001.

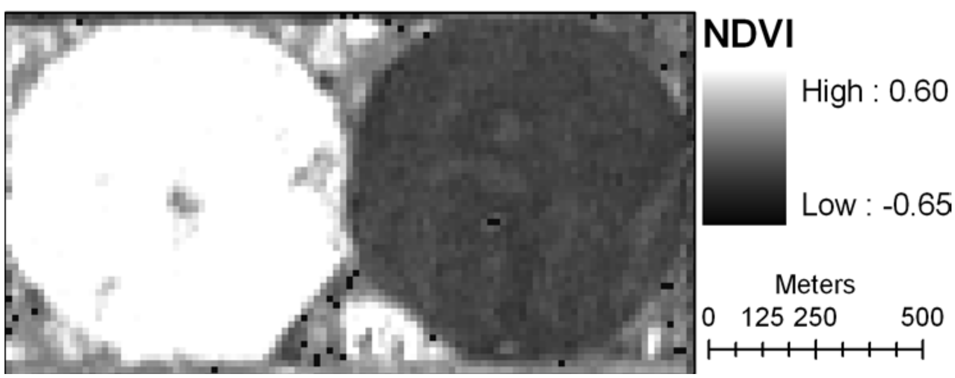

Figure 2. Example of Normalized Vegetation Difference Index (NDVI) for two fields. Vegetation indices are used to estimate green fraction vegetation cover of individual fields enhancing the ability of identifying potential sites for ephemeral gully formation. Data generated using ASTER scene acquired on 2001-05-16 over Kansas, USA.

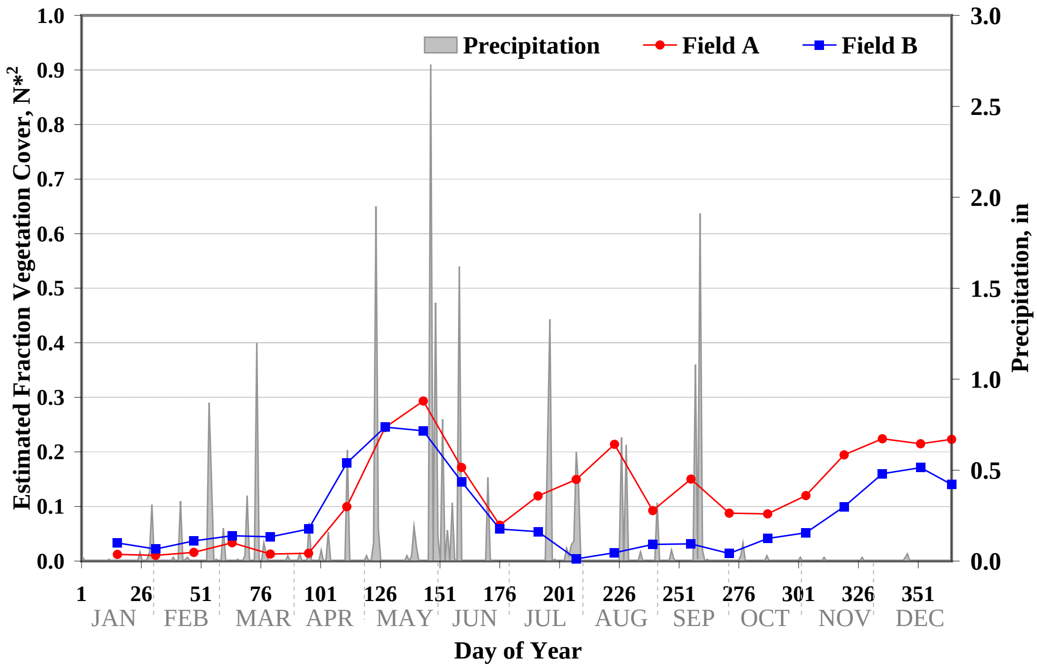

Figure 3. Estimated fraction vegetation cover of two fields obtained from remotely sensed results contrasted with daily precipitation amounts. The wide spatial coverage and high temporal resolution of satellite-borne optical sensors offer an alternative tool to monitor individual field management for ephemeral gully investigation. Data generated using 16-day composites of MODIS NDVI product (MOD13Q1) for year 2001.

EXAMPLE KANSAS WATERSHED APPLICATION STUDY CONTAINING GULLY SEDIMENT SOURCES

The Cheney Lake Reservoir is a major source of water for the city of Wichita, KS and is located in south central Kansas near the town of Hutchinson. The watershed drainage area into the reservoir was chosen by the USDA as a Special Emphasis watershed in their Conservation Effects Assessment Project (CEAP) to evaluate the importance of specific agricultural conservation-related problems and the impacts of these problems on water quality that may be overlooked by the larger-scale, national assessment effort of CEAP.

The total drainage area for the watershed is more than 1,000 sq. mi. The watershed is dominated by agricultural landuse consisting of cropland and rangeland. The average annual precipitation varies from close to arid to nearly humid. The average annual precipitation is 29 inches for the entire watershed. Only a small fraction of the precipitation reappears as streamflow in the river before it enters the reservoir.

Cheney Reservoir is currently designated a high priority impaired water body under the Clean Water Act, with impairments listed for eutrophication and sedimentation. Goals have been established to reduce sediment loadings by 40-

45% for the watershed. All AnnAGNPS modeling within this project has been validated and calibrated to the U.S. Geological Survey data collected in 1996--2000. A critical aspect of the NRCS investigation will be to determine the effects on reducing sediment loadings from the Conservation Reserve Program, tillage practices, irrigation-scheduling practices, and the contribution of sediment from ephemeral gullies within this watershed.

Potential Sources of Sediment

Sediment is a concern within the Cheney Lake watershed with regard to both water quality and to reservoir storage capacity. Cheney reservoir was designed to provide sediment storage for 100 years. Sources of sediment within this agricultural watershed include sheet and rill erosion, ephemeral gully erosion, and streambank erosion.

Sheet and rill erosion is defined as the removal of soil from the land surface by rainfall and runoff detachment. The visible effects of sheet and rill erosion can be removed by tillage practices. Subsequent erosive actions may produce rills in different places then previous erosion events. Typically, sheet and rill erosion creates shallow, parallel channels that are uniformly spaced and sized. Examples of management practices to address sheet and rill erosion include conservation tillage, gradient terraces, and field buffers.

Ephemeral gully erosion results from concentrated flow upstream from incised channels. Soil is removed along a narrow flow path to a depth where a less-erodible layer may occur. These temporary gullies may be obscured by tillage but they will reform in the same location at the next rainfall event (Figure 4). As soil is moved into the voided area by tillage, an area wider than the actual gully is damaged. Erosion from ephemeral gullies beyond the calculated sheet and rill

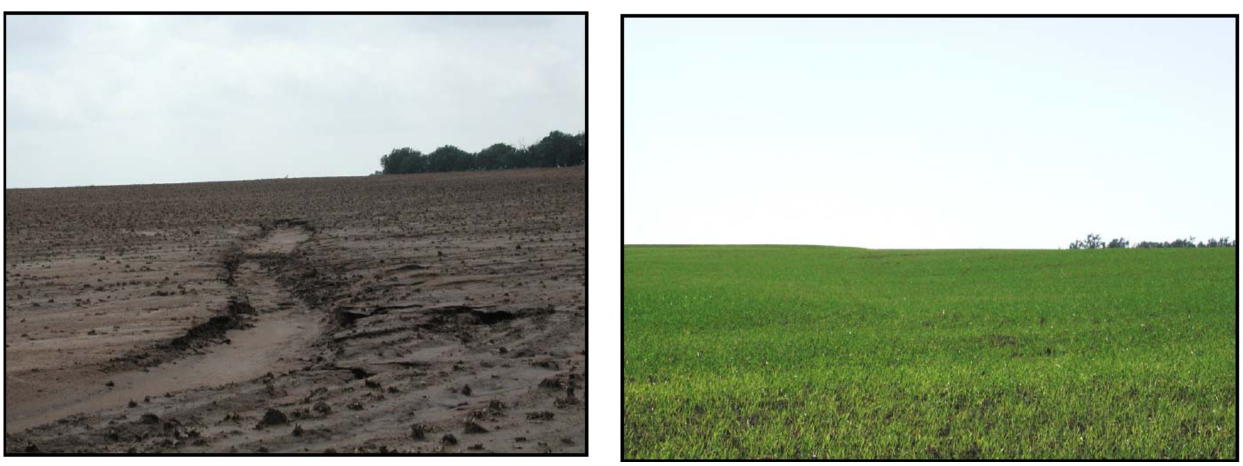

Figure 4. Visible ephemeral gully on the left (August 26, 2005) and the same location on the right (October 17, 2005) with the ephemeral gully obscured by vegetation and other field operations.

erosion loss are not included in the Universal Soil Loss Equation (USLE) model (Wischmeier and Smith, 1978) or RUSLE. Figure 4 shows the same crop field in the Cheney Lake Watershed on August 26 and October 17 of 2005. The ephemeral gully is obscured later in the year by tillage and planting operations.

Investigation of Sediment Origin

As watershed managers attempt to reduce suspended solids within the Cheney Lake watershed stream system, the primary sources of sediment should be evaluated. Early modeling efforts in the watershed assumed two primary sources – stream bank loss and soil erosion as calculated using the Universal Soil Loss Equation (USLE) model.

Estimates of stream bank erosion were based on a 1996 investigation by the Kansas Natural Resources Conservation Service state geologist. A survey of the North Fork Ninnescah stream system at that time determined that less than 15% of the sediment load originated from the stream banks. When the AnnAGNPS model results of the Cheney Lake watershed were validated with U.S. Geological Survey stream monitoring data, there was a gap between the sediment load predicted by the model and the actual sediment load measured by USGS. Other outputs predicted by the model were in agreement with the USGS data. Figure 5 shows the difference in tons of sediment measured by USGS and the sediment predicted by the model. On investigation it was determined that the USLE model did not capture erosion as a result of ephemeral gullies within crop fields. The hypothesis was that ephemeral gullies would prove to be the source of the sediments that were not accounted for within the early modeling studies. Within the CEAP investigation, the AnnAGNPS model has been enhanced with the addition of a method to account for ephemeral gully erosion. NRCS documented over 1,000 ephemeral gully locations after examining aerial photographs (Figure 6), which were then simulated with AnnAGNPS. The predicted results of the CEAP modeling closely matched the predicted sediment load with the actual measured sediment load after utilizing the ephemeral gully components of AnnAGNPS and calibration.

With the contributions from ephemeral gullies included in the simulations, the investigation ranked land area within the watershed according to its predicted sediment contribution to the overall loading of the watershed. Using this ranking, relationships between the percentage of sediment load and the percentage of contributing cells were developed. Figure 7 illustrates this relationship showing that roughly 10% of the 200-acre cells in the watershed are contributing approximately 70% of the sediment load as a result of sheet and rill and gully erosion. Approximately 35% of the sediment load in this watershed could be eliminated by treating all of the ephemeral gullies. The areas representing 10% of the watershed that contribute 70% of the sediment are shown in Figure 8. Areas can also be highlighted to indicate those that are contributing less than the highest 10% but higher than the mean sediment contribution of the watershed at the outlet.

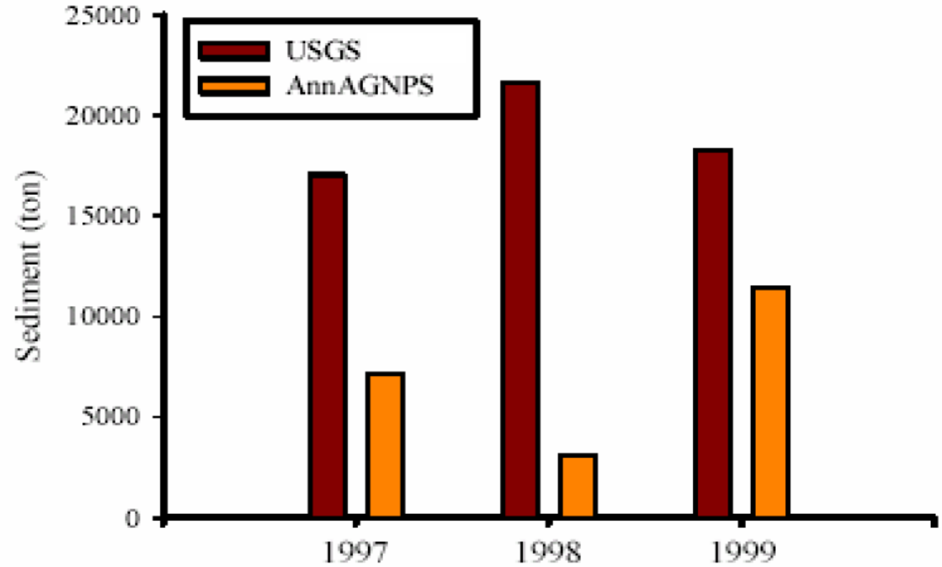

Figure 5. Comparison plots of observed and predicted sediment yield from AnnAGNPS simulations without ephemeral gully features at the USGS gauging station (07144780) on the North Fork Ninnescah River above Cheney Reservoir during 1997–1999.

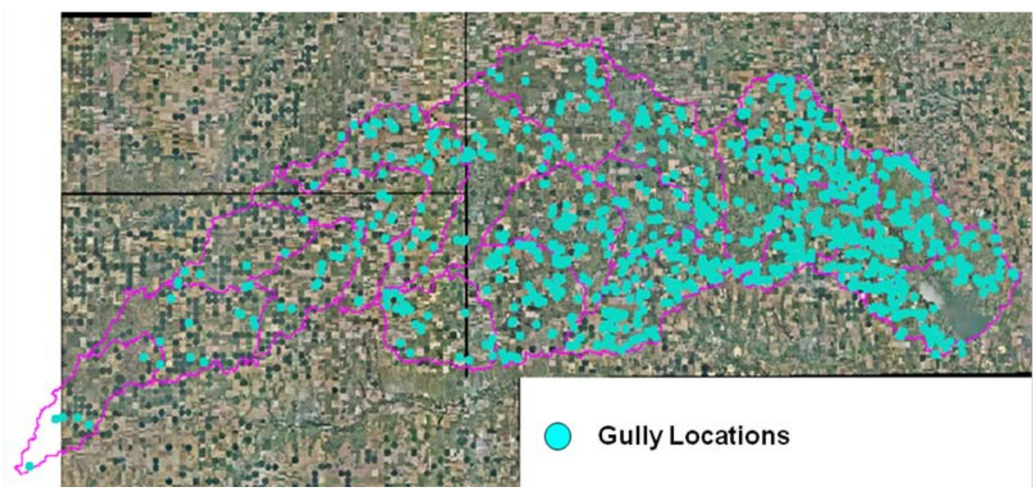

Figure 6. Location of tillage-induced ephemeral gullies identified by NRCS within the Cheney Lake Watershed.

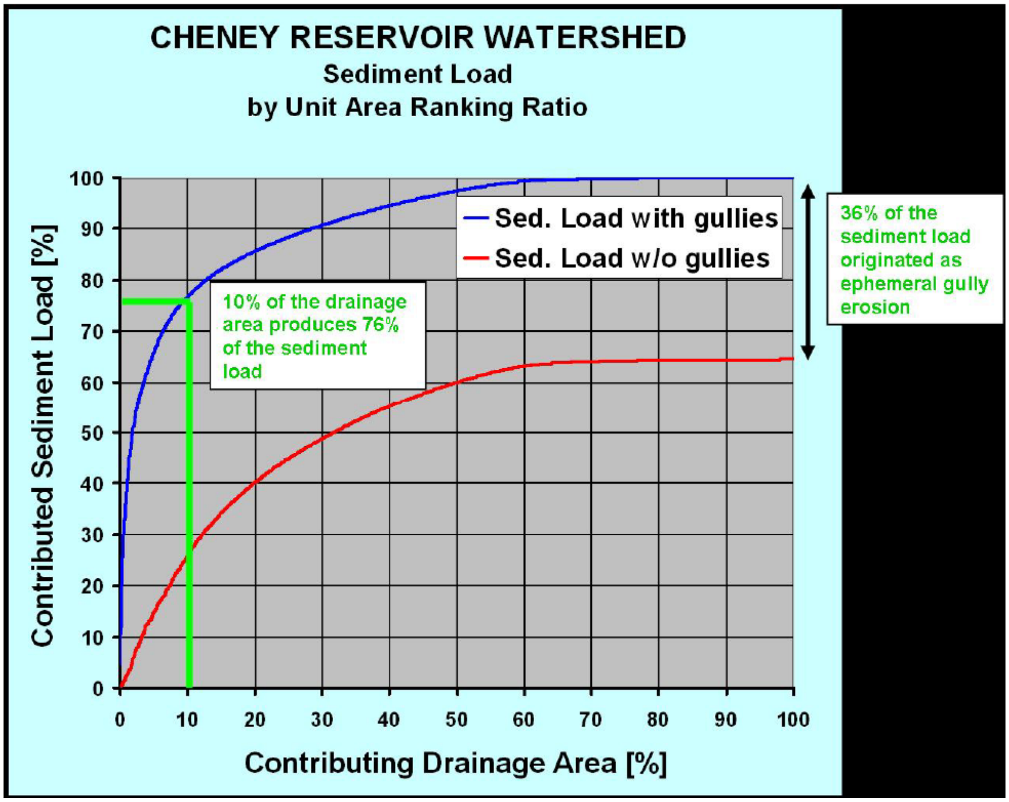

Figure 7. Sediment Load Contribution by Ranked Unit Areas

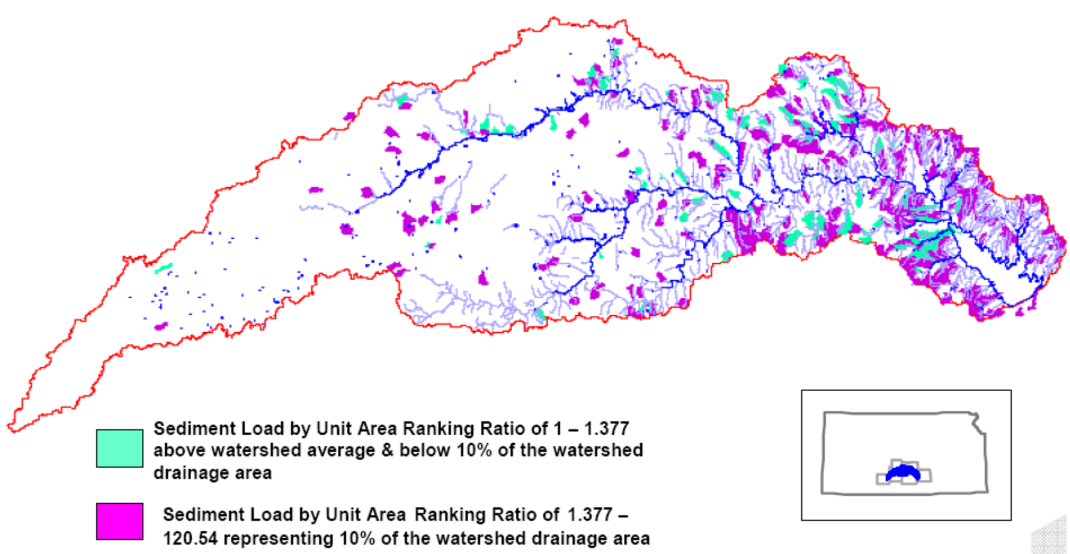

Figure 8. Cheney Lake Watershed ranking of sediment load by unit area with respect to the watershed outlet.

CONCLUSIONS

Sources of sediment from sheet and rill and gully erosion can be evaluated with enhanced gully components recently developed within the USDA AnnAGNPS watershed pollutant loading model. Utilization of the model on the Cheney Lake watershed in Kansas illustrated the impact gullies have on total sediment load. Results showed that 10% of the watershed is contributing 70% of the sediment load to Cheney Reservoir with a significant portion of the sediment source produced from ephemeral gullies in crop fields. If all ephemeral gullies within the watershed are treated with conservation practices specifically designed to address this type of erosion, the sediment load to the reservoir could be reduced by 35%. Although, targeting the highest sediment producing areas would not require treating all gullies in the watershed in order to reduce sediment loads significantly. The findings of this investigation could be used to make significant changes in the implementation of conservation measures by implementing practices only where specifically needed to address sheet and rill or gully erosion.

The voluntary implementation of conservation practices to address specific sources of sediment in specific locations within the watershed will result in more rapid water quality improvement than random voluntary implementation of conservation practices. When funding and technical assistance are not available, the ability to identify and rank the pollutant sources will be critical in focusing assistance in areas that will provide the greatest improvements.

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