Estimating Erosion, Water Quantity and Quality Changes in Response to South Dakota Grassland Conversion

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ABSTRACT

South Dakota is a mosaic of grasslands, wetlands, and cropland. A continued shift from grassland to cropland has occurred over the past 10 years and is expected to continue for the next 50 years. The rate of future conversion may vary greatly depending on economics, policy, and demographic factors. In any case, land conversion will influence cumulative erosion from arable soils which could potentially impact stream and river hydrology and water quality. Quantifying future changes for these three externalities is important to understand the possible consequences of grassland conversion. Annual grassland conversion has been captured using a recently developed thematic map of the contiguous United States (1947-2062; USGS 2014). Spatial land cover, soils and climate data have been delineated by hydrologic unit codes 10 (HUCs) and integrated via subscripts to parameterize HUC 10 (sub-catchments; 53 unique catchments) and HUC 6 (total catchments; aggregate of the 53 HUC 10s) water-catchments. The model forecasts future annual erosion and water quantity and quality changes under different potential future grassland conversion rates over the next 50 years, giving insight for future landscape scale externalities of grassland conversion in South Dakota.

INTRODUCTION

Land use change can alter the production and delivery of ecological goods and services. Since the 1900's, new farming technology (Dimitri et al., 2005) and increasing grain demands (Clay et al., 2014) have accelerated the expansion of land conversion from grassland to cropland in the Midwestern U.S. The rates of this type of land conversion have increased in the past decade (Clay et al. 2014; Claassen 2011). Wimberly and Wright (2013) found that rates of conversion from grassland to cropland in the Midwest between 2006 and 2011 (1.0-5.4% annually) were comparable to the deforestation rates in Brazil, Malaysia, and Indonesia (Lepers et al., 2005 & Hansen et al., 2008). Accelerated grassland conversion may impact ecological goods and services by increasing soil erosion rates, changing hydrology patterns, and decreasing water quality.

Grassland conversion and other types of land use change have contributed to increased soil erosion worldwide (Pimentel, 2000; Lal 2004). Approximately 75 billion tons of topsoil are lost each year from global agriculture production, and roughly 6.9 (9.2% of worldwide) billion tons of soil are lost each year in the United States (Pimentel, 2000). Erosion by water can be sheet or rill erosion or both, which typically occurs during intense rainfall events (Larson, Lindstrom and Schumacher 1997). Sheet erosion is a uniform removal of soil in thin layers and rill erosion is water concentration in streamlets or head cuts (Horton 1945). Both sheet and rill erosion may reduce nutrient uptake by plants, decrease rooting depth, diminish water-holding capacity of soils, and increase runoff (O'geen and Schwankl, 2006).

Similar to erosion, hydrologic processes are impacted by grassland conversion to cropland. Lower soil permeability in cropland has been shown to reduce water infiltration by five times than that of grassland (Bharati et al. 2002; Gerla 2007). Diminished plant water uptake (transpiration) and soil infiltration alters surface runoff, evapotranspiration rates, baseflow of lotic systems within the watershed, and groundwater storage (Foley et al., 2005). Changes in hydrology may also reduce groundwater storage as accelerated runoff reduces subsurface water infiltration (Rosegrant, Cai & Cline, 2002). Consequently, stream and river flow regimes and discharge typically increase as natural vegetation is cleared (Costa, Botta & Cordille, 2003).

Increased erosion and hydrologic changes typically result in sediment (sand, silt and clay particles) being transported by overland-flow into streams and rivers, which then end up either suspended or deposited in waterways. Sedimentation is a naturally occurring event in stream and river morphological processes (Leopold et al., 1964) and is most influenced by flow regimes as flow velocity determines deposition (Waters, 1995), since anthropogenic disturbances increase sedimentation rates (Polyakov, Nichols, and Nearing 2016). Grassland converted for agricultural use alters typical surface slopes and stream gradients, making them more susceptible to erosion by water, which further induces deposition of sediment in waterways (Lowdermilk, 1953, Tremble, 2008). Over time, sediment movement and deposition increases total suspended solids (TSS) in the water column, which reduces water quality. Excessive sedimentation causes negative effects including alteration of wetland plant species composition (Mahaney, Wardrop, and Brooks, 2004) and decreased storage capacity of reservoirs, rivers, and streams (Yang, 2010). Sedimentation can also fill in interstitial spaces of substrates (Berkman and Rabini, 1987), decrease light penetration (Irving and Connell, 2002), and alter nutrient cycling processes (Covich et al., 1999) in aquatic ecosystems (Schlosser, 1991).

Presently, land use changes are happening in South Dakota, an area that is unique in soil, topography, and climate. South Dakota is roughly bisected along a latitudinal line by the Missouri River (Figure 1). Distinct differences between the eastern and western portions of the state include precipitation, geology, topography, and consequently, land use. The eastern portion of the state is primarily within the Prairie Pothole Region (PPR) and receives an annual average of 50-60 cm of precipitation (Hubbell et al., 1987). The PPR was created during Cenozoic period when expanding and receding glaciers deposited sediments and formed kettles (i.e., potholes) throughout the region (Samson and Knopf 1994; see http://www.sdgs.usd.edu /geologyofsd /geosd.html for map). Historically, this area was used for grazing livestock, but now much of the once native prairie has been converted to cultivated land (*Zea mays*, *Glycine max* & *Tricticum aestivum*.; Samson and Knopf, 1994) . Western South Dakota is relatively drier and receives 40-50 cm of precipitation annually (Hubbell et al., 1987). The geology of this region is composed of older Mesozoic sediments, including eroded clay, shale, and sandstone (see http://www.sdgs.usd.edu/geologyofsd/geosd.html for map). Western South Dakota is primarily rangeland consisting of rolling hills and eroded stream valleys, but also includes the Black Hills (Griees, 1996). Throughout the state, grassland conversion to row crop agriculture has accelerated, particularly in the eastern half of the state, but some conversion has occurred in the central and westerns portions (Wimberly & Wright, 2013; Johnston, 2014; Figure 1).

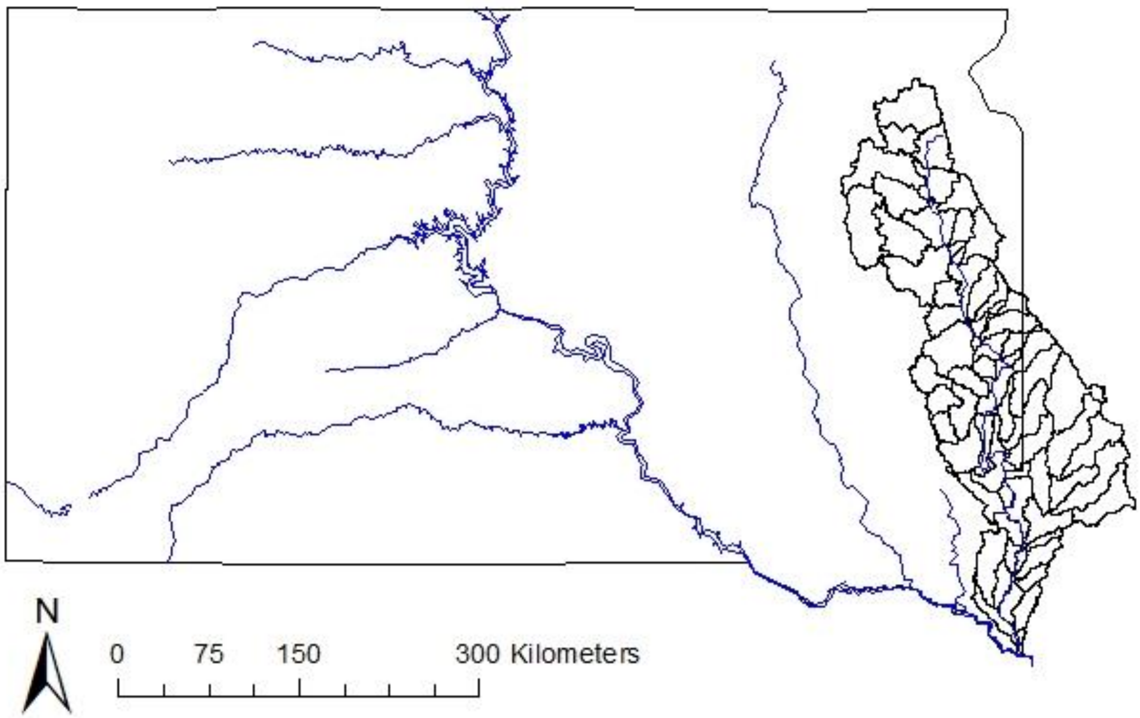

Figure 1. Map of the U.S. state South Dakota. The Big Sioux River (BSR) water catchment is located on the eastern boundary of the state. This area is approximately 22,910 km^2 or 2,291,000 ha. The dominant soil order is Mollisol with an average slope of 0-3%.

- The term Hydrologic Unit Code (HUC) represents the geographic and sociopolitical boundaries of a water catchment. A HUC6 represents the entire BSR and HUC10s represent small water catchments within the HUC6.

- The HUC6 BSR water catchment in our study has been delineated HUC10 catchments, there are 53 unique HUC10s within the BSR (Figure 1).

Accelerated grassland conversion to cropland is a complex problem that may have future unintended consequences for the environment, which include changes in sheet and rill erosion rates (i.e., water driven erosion), hydrologic regimes (i.e., surface water runoff), and water quality (in this case, TSS). Turner et al. (2016) modeled various policy, cultural, and economic scenarios that influence cropland expansion rates in the Northern Great Plains and the subsequent impact on soil externalities using System Dynamics. Forecasted scenarios indicated that these land use changes may potentially pose a risk of environmental externalities. An example of one such scenario is the elimination of the Conservation Reserve Program (CRP).

Removal of CRP led to externalities of the same magnitude estimated for the Dust Bowl Era (Turner et al., 2016). Externalities and risk have been captured using a dimensionless index called Soil Environmental Risk (SER). It is uncertain how these externalities could be realized on the landscape. Thus, quantitative data for perceived environmental externalities, which are soil erosion (tons/ha/yr), water quantity (m^3/s/yr), and water quality (tons/ha-meter/yr), are currently lacking. Specific quantification of estimated changes in these specific externalities would aid in further evaluating the risk of accelerated grassland conversion now and into the future, especially as economics, policies, and demographics continue to change. Focusing questions have been developed to address these potential environmental externalities.

Focusing Questions:

1. Will accelerated grassland conversion to cropland result in environmental externalities that alter current and future erosion, hydrology, and water quality (as indicated by TSS) in South Dakota?

2. What is the behavior and structure of the system and what are the highest leverage points that influence long-term erosion, hydrology, and water quality (TSS) changes in four South Dakota water catchments?

METHODS

The Approach: System Dynamics

A System Dynamics approach was used to address the complexity of grassland conversion, erosion, hydrology and water quality changes in the Big Sioux River Water Catchment in the U.S. state of South Dakota.

1) Problem Articulation

a) Theme Selection

Presently, the water-catchment in this study has been and is being altered from natural conditions (grasslands) into intensively managed agricultural land, primarily cropland. This could potentially change soil erosion, water quantity (regimes), and water quality externalities. Turner et al. (2016) indicated agriculture policy and production demands play a significant role in land use/conversion decisions by reinforcing continued grassland conversion in South Dakota (Johnston, 2013; Wimberly and Wright, 2013). Furthermore, grassland conversion is estimated to approach maximum limits by 2062 in the most productive soil classes [Land Capability Class (LCC) 1 – 3] and marginally increase in less productive classes [LCC (4-8)]. Reaching these limits may push the land past tipping points, causing negative unintended environmental consequences that exceed tolerable magnitudes of erosion, hydrologic regimes, and TSS. Therefore, the problem is that unmitigated grassland conversion to cropland may cause environmental risk that impairs soil suitability, hydrology, and water quality in South Dakota. (see appendix for key variables description, Table 1 and Table 2; time horizon description).

2) Formulation of the Dynamic Hypothesis

a) Initial Hypothesis Generation

To successfully articulate the problem for environmental risk (erosion, water quantity, and quality) a DH was developed that best describes the problematic behavior over time. The DH will attempt to capture the core structure and feedback dynamics of water quality changes by combining key variables from existing erosion and hydrologic models. There is no definitive theory to explain how grassland conversion impacts soil erosion, water quality, and quantity, but the literature supports certain variables that are most frequently used to describe the rates of change for these externalities. These variables were first used in the Universal Soil Loss Equation (USLE), which eventually became the Revised Universal Soil Loss Equation 2 (RUSLE2). The RUSLE2 has since been adopted as the basis of most erosion and hydrologic models (i.e., the model is universal). The basic components of the RUSLE2 are described by the formula:

$$A = RKLSCP;$$

Where A is average annual soil loss from rill and interrill erosion caused by rainfall and its associated overland flow expressed in tons/hectare/year; R is climate erodibility; K is soil erodibility measured under a standard condition; L is slope length; S is slope steepness; C is cover management (dimensionless); and P is support practices (dimensionless; Widman, 2004).

b) Endogenous Focus

The following statement is our endogenous articulation of the hypothesized structure: Land use change from grassland to row crop agriculture has cascading effects within the plant-soil-water continuum at the field level, including: plant cover, rooting structure, plant residue, soil aggregate stability, and soil permeability. The cumulative effect of these changes influence surface water hydrology and soil erodibility and impacts soil quality, which subsequently alters natural (baseline) total suspended solids in streams and rivers. Unforeseen consequences from soil loss (aggregate sheet and rill erosion; tons/ha/year), hydrologic changes (too much or too little; m^3/s/year), and impaired water quality (TSS; tons/ha-m/yr) may reduce the functionality of ecological goods and services. Impairment of these resources may limit hectares of land available for production in the form of mandates to mitigate environmental externalities, for example removal of land in production (e.g., CRP) or that degradation has made vulnerable land unsuitable for agricultural production (see appendix for Dynamic Hypothesis Causal Loop Diagram; Figure 2).

3) Formulation of a Simulation Model

a) Specification of Structure and Decision Rules

Structure and decisions rules for this study will be based on the existing methodologies such as RUSLE2, the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), and the Soil Water Analysis Tool (SWAT). These models contain specific computations, coefficients, derivatives, and spatial inputs to develop a model capable of estimating erosion rates, hydrologic changes, and TSS. For example, the RUSLE2 equation contains climate, soil, cover, and management indices for the calculation of rill and sheet erosion estimations and the SWAT equation includes overland-flow calculations to determine sediment movement.

b) Estimating Parameters, Behavioral relationships and Initial Conditions

Estimation of parameters, behavioral relationships, and initial conditions are important to consider capturing dynamic complexity in the model to achieve its purpose while keeping the model manageable in terms of size (see appendix Table 3; Sterman, 2000). One example of estimating parameters is water flow, which we parameterized by the units of cubic meters per sec (m^3/s) to capture annual discharge for each catchment. Next, behavioral relationships were identified. For example, hydrologic behavior encompasses precipitation (inflow; m^3/s), stored water (storage; m^3) and discharge (outflow; m^3/s) as observed in streams, rivers, and lakes. Chow et al. (1988) define this simple behavioral relationship known as a water balance equation:

$$\frac{dS}{dt} = I - Q$$

Where, dS = change in storage (m^3); dt = rate, t = time (seconds), I = inflow (m^3/s) and Q = outflow (m^3/s). Initial conditions include soil permeability which determines the rate of water absorption (in/hr) into the soil. Pristine, uncultivated grassland are initially very permeable, until altered by tillage and other cultivation practices.

c) Model Purpose and Boundary Consistency Test

Model formulation was completed by testing for consistency with the model's purpose and boundaries as data was added. Testing for consistency and model purpose ensured that the data were at the appropriate level of detail (e.g., field scale ha or landscape scale km^2) during model construction. This helped build confidence in the model and aided in identifying assumptions. However, challenges arose when attempting to formulate the model as some data were not available in the literature. Data challenges were addressed with validated indices to provide close approximations for soil plant cover, soil quality, management practices, and other factors (e.g., total suspended solids and plant growth dynamics; Gray et al., 2016). For example, information on Best Management Practices (BMPs) implementation exists for the Bad River water-catchment, but an index was built to quantify the potential relative effect that each specific BMP (e.g., livestock integration or no-till) may have on landscape scale externalities (Smart et al., 2010; Kamp, 2012).

4) Model Overview

Major components required to estimate changes in erosion, water quantity and water quality have been identified as a) crop and grass production, b) water balance, c) management, d) erosion, and e) sediment deposition and total suspended solids (see appendix for data collection and processing; Figures 4-8). Associated feedback loops, key equations and insights are discussed in the following sections (Figure 8).

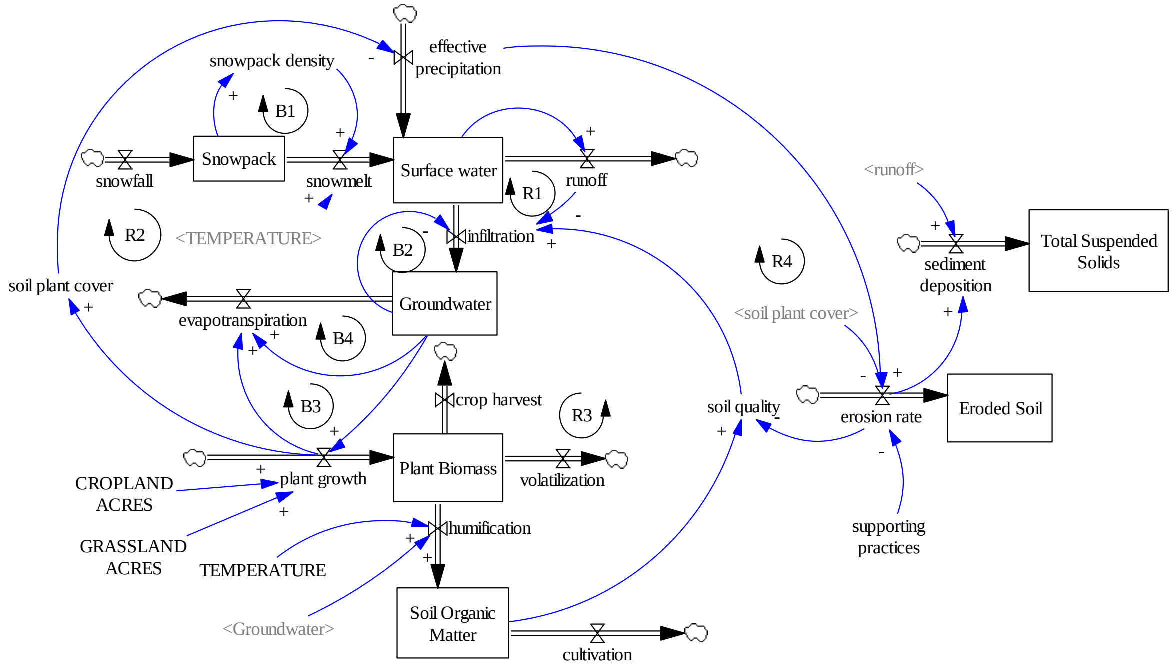

Figure 8. Stock and Flow diagram of the SD model. Exogenous variables are denoted in capital letters significant reinforcing (R) and balancing (B) loops have been labeled throughout the following text for visual reference for loop descriptions

a) Crop and Grass Production

Yearly land cover characteristics for crops and grass include: planting date, growth rate, and harvest to capture plant biomass (Figure 4). Pulse train functions were used to simulate annual crop planting, growth, and harvest times in South Dakota (see Appendix Figure 9). Annual grass growth was regulated by established growth curve data for the region as grasses reestablish themselves. Grass harvest was delayed a month and then harvested monthly throughout the growing season (see Appendix Figure 10). Soil temperature and moisture are the two most limiting factors for plant growth. Temperature in the form of growing degree days (GDD) represents accumulated heat required for plants to reach physiological maturity represented by this equation:

$$GDD = \frac{\text{Maximum Daily Temperature} + \text{Minimum Daily Temperature}}{2} - 10$$

Specific GDD physiological growth requirements (see Appendix Figure 11 and Table 4) were calculated using a lookup function for each crop type to determine plant soil cover (%) and plant growth (kg/day). Groundwater and plant growth share a linear relationship and were used to regulate plant growth (B3; Figure 3). Plant growth and groundwater dynamics were calculated using this equation:

$$(plant\ growth * plant\ available\ water) * plant\ acres * planting\ delay$$

b) Hydrology

Water Inflow and Storage. The primary object of the hydrologic component is to estimate discharge (m^3/s/year; see Appendix Figure 12). Key hydrologic drivers are snow (m depth storage) and precipitation (cm/day) calculated with the following equation:

$$Surface\ Water\ Volume = (\ water\ inflow\ (m) \times\ area(ha))\ \times\ \frac{10000\ m^3}{ha}$$

Snowfall exogenous data were adjusted to a snow to volumetric water equivalent (see snow water equivalent [SWE] equation) and then stored until average daily temperature was above 1.7℃, allowing snowmelt to occur. Snow density increases throughout the winter and spring due to gravitational settling, wind packing, melting, and recrystallization (NRCS 2017; B1; Figure 3) and was calculated using this equation:

$$SWE = Snow\ Depth\ \times\ Snow\ Water\ Density$$

Precipitation was stored as surface water during winter months when temperatures were below 1.7℃ (ice or depression storage). Precipitation events not affected by temperature were influenced by interception using the leaf area index (i.e., a dimensionless index of rain intercepted by plant leaves; Ostrem et al., 2016) and then infiltrated into the soil. Leaf area index received feedback from soil plant cover as cover limits precipitation from becoming effective precipitation (i.e., precipitation that reaches the soil; R2; Figure 3). Once water reaches the surface water stock, it is abstracted into the ground through infiltration unless average daily temperature is below 0℃ or if soil is at field capacity (i.e., limit of soil pore space [porosity]). Infiltration was calculated by abstracting surface water until groundwater storage reached field capacity providing a negative feedback, decreasing infiltration rate (m^3/Day; B2; Figure 3; Miller and Gardner). Infiltration is shown in the following equation:

IF THEN ELSE(Surface Water > 0, Surface Water * (infiltration coefficient lookup) * field capacity, 0)* freezing temperature limit

Surface Water Runoff. Water balance outflows include surface water runoff (m^3/day), evapotranspiration (mm/day), and evaporation (mm/day). Surface water runoff was calculated using a modified version of the rational method show in this equation:

$$Q = CiA$$

Once the runoff coefficient (C) has been determined the infiltration coefficient can then be calculated by using the following equation:

$$Infiltration\ Coefficient =\ 1 - C$$

Thus, surface water runoff was computed using this equation:

IF THEN ELSE (water inflow > 0, Surface Water * runoff coefficient, 0)* freezing temperature limit

The rational method has been used since the mid-Nineteenth Century (Pilgrim, 1986; Linsley, 1986) and has valid criticisms about its adequacy. However, the method continues to be used for its simplicity (Chow et al., 1980). Components of this method were used to approximate peak discharge. The rational method uses C to estimate peak runoff per event. The runoff coefficient incorporates a weighted land factor value which includes relief, soil infiltration, vegetative cover and surface storage. Once C is determined, rainfall intensity (*i)* and watershed area (A) are multiplied to determine the water inflow rate. Thus, CA*i* expresses the relationship of peak discharge Q (m^3/s) to inflow during the time of the rain event. This method was modified by calculating total daily rainfall (cm/day) in place of intensity (*i;* cm/hour) as hourly data for this timescale is limited and requires extraneous processing time. Feedback linkages indicate that as C increases less water is infiltrated as the percent of infiltration equals 1 - C (R1; Figure 3). Runoff was limited when there was no water inflow (snowmelt or effective precipitation) and by temperature below 0°C.

Evapotranspiration. Crop and grass evapotranspiration (ET) rates were used as groundwater outflows (m^3/day; see Appendix Figures 14). The Hargreaves method was used to calculate daily ET shown in this equation:

$$ET_0 = K_{ET} \times RA \times TD^{0.50} (T \text{ °C} + 17.8)$$

This method provides a reliable rate of ET and is comparable to other methods such as the Penman-Montieth (Hargreaves and Samani, 1985). The simplicity of the Hargreaves method was preferable as complex ET methods require additional parameters. This method uses crop or grass specific evapotranspiration coefficient (K_{ET}), extraterrestrial radiation (RA), mean maximum temperature minus mean min temperature (TD), and mean temperature (T °C). Plant growth is required for ET to occur and provides a feedback to ET during the growing season (B3). Groundwater generates feedback to regulate ET by adjusting it based on soil moisture (%; i.e., groundwater availability) show in the following equation:

$$E(s) = \begin{cases} E_w \dfrac{S - S_h}{S_w - S_h}, & S_h < S \leq S_w, \\ E_w + (E_{max} - E_w) \dfrac{S - S_w}{S^* - S_w}, & S_h < S \leq S^*, \\ E_{max} & S^* < S \leq 1, \end{cases}$$

Soil water (S) is categorized by plant stress (S*), wilting point (S_w), and hydroscopic (S_h). Soil water and ET decrease until only evaporation (E) is possible, because water at the hydroscopic level is unavailable for plant transpiration (Laio et al., 2001). Soil texture (e.g., clay, loam, sand; Dingman, 1994; Lau and Katul, 2000; Cosby et al., 1984) determines the potential water availability creating a feedback linkage for ET levels throughout the growing season (B4; Figure 3; see Appendix Figures 15).

c) Management

Soil cultivation consists of management practices that alter soil organic matter, soil porosity, and soil erodibility. Crop cultivation practices encompass a large spectrum from conventional-tillage to no-till. Convention-till practices can decrease soil organic matter over time, while no-till often leads to a net gain of organic matter overtime (Rhoton, 2000). Grazing practices follow a general rule of "take-half leave-half" to maintain the ratio of above and below ground biomass (roots and canopy). Overgrazing can also decrease soil organic matter overtime (Schipper et al., 2017). Soil organic matter increases soil water holding capacity by as much as 60,567 liters per hectare increasing soil quality (R3; Figure 3; porosity). Changes in percent organic matter were calculated by the loss of soil organic matter from tillage type and regulated by average temperature being above 10℃ for microbial processes to occur (volatilization). Soil organic matter in the model calibration was kept between 1-2% for cropland and between 5-7% for grassland. The percent organic matter can then be multiplied by the rate of loss (outflow) from cultivation (i.e., cultivation decreases biomass available for soil organic matter production and increases the rate organic matter breakdown; Rhoton, 2000). Soil organic matter loss is calculated in the following equation:

IF THEN ELSE(AVERAGE TEMPERATURE >10, soil organic matter loss rate* Organic Matter, 0)

d) Erosion

Erosion estimations (tons/ha/year) were derived by integrating the RUSLE2 (Table 3; see Appendix Figure 15) into the model. Aggregate rill and sheet erosion estimations from the RUSLE2 should not be confused with sediment deposition into a stream or river (Foster et al., 2002). The RUSLE2 equation (see equation in section 2) has been partitioned into exogenous variables R, K, LS, and P and endogenous C creating a dynamic nature to adjust for erosion per rainfall event (Cakula et al., 2012). Soil erodibility (K), slope length and slope steepness (LS), and supporting practices (P) were integrated into each HUC10 from existing data developed by the United States Department of Agriculture (Wischmeier and Smith, 1978). The cover (C) feedback linkage decreases erosion (R5; Figure 3). Erosion impacts the organic matter and topsoil (first 0.3m of topsoil), which typically have the largest amount of pore space (i.e., porosity), reducing soil quality (R4; Figure 3).

e) Sediment Deposition and Total Suspended Solids

Sediment deposition (tons/ha; deposition) into a stream or river was computed using the Vanoni power function that expresses the sediment delivery ratio from erosion per event that reaches ephemeral streams, gullies, or rivers (i.e., deposition into a waterway), which is proportion to area (km^2) of each HUC10 (Vanoni,1975). The sediment delivery ratio is shown in the following power function:

$$Sediment\ Delivery\ Ratio = 0.42\ Area^{-0.125}$$

Once sediment enters a stream or river, it is either suspended in the water or settles to the bottom. Existing total suspended solids (kg/l) levels are altered by changes in water discharge (m^3/s) and were estimated using typical water discharge and sediment relationships specific to the region. Eroded sediment brought into a stream or river system during intense rainfall events or spring snowmelt were then added to this baseline TSS (see Appendix Figure 16).

Fifty-three HUC10 water catchments were simulated using a "HUC" subscript. Data for each subscript were brought in sequentially for "HUC1" to "HUC53" from Excel™ into Vensim™. Catchments were then interconnected by stream order and finally joined into the BSR for a total catchment (HUC6) estimation of discharge, erosion, and TSS.

5) Test the Model: Calibration Results

The model was evaluated performing reference mode comparison, sensitivity analysis, and extreme condition tests for key variables to provide confidence in the model (e.g., physical boundaries such as non-negative water). Reference mode tests for Skunk Creek (HUC10; Figure 17) indicated that discharge estimates matched the structure and behavior of the system, R^2 (.44). It was observed that once the water balance reached an equilibrium the correlation coefficient increased (.58). Daily precipitation data is difficult to approximate for a specific HUC10 catchments due to availability of recorded data. Therefore, select calibration periods were chosen where the strongest correlation existed between precipitation and discharge. The reference mode tested for this example was simulated from February 1977 to November 1979.

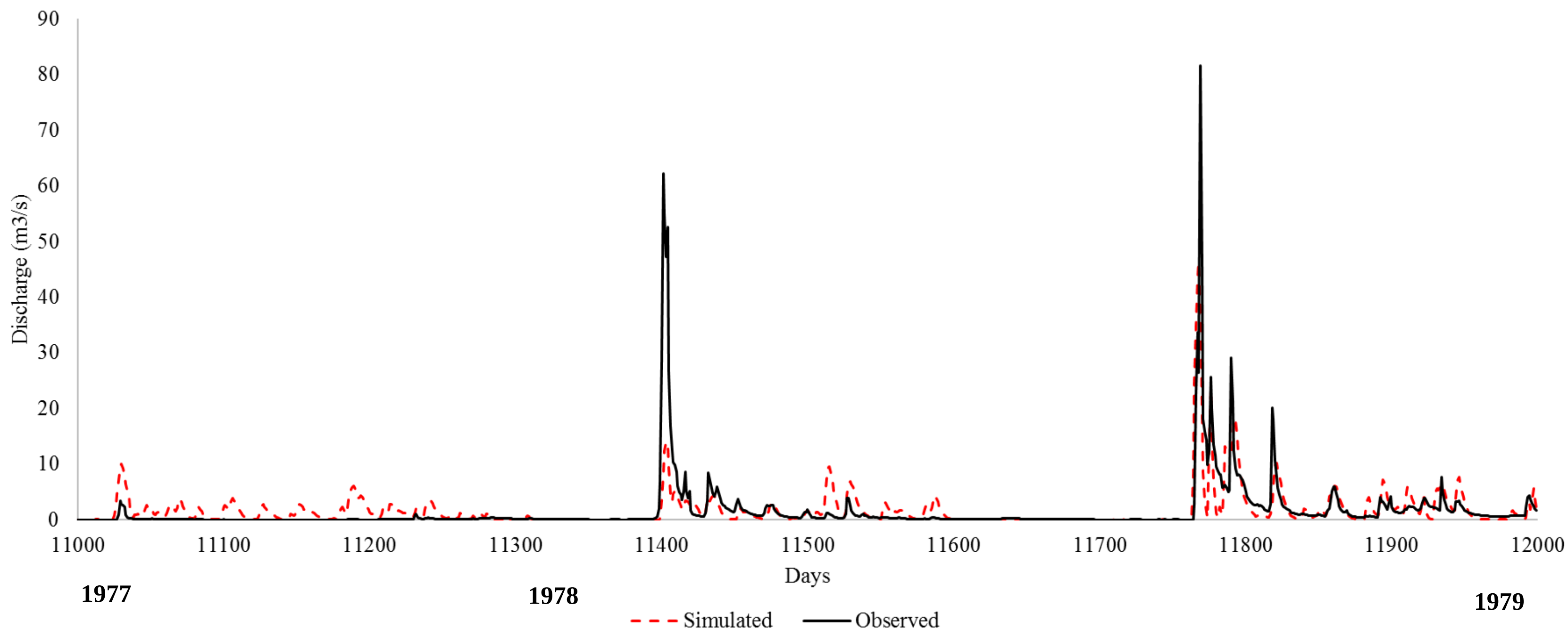

Figure 17. Reference mode test comparing the simulated and observed discharge of Skunk Creek (HUC10) from February 1977 to November 1979. Results indicate that after a warm-up period estimates improved. Peaks are a result of snowpack melting in the spring, which is a dominant characteristic of the BSR's hydrologic regime.

A sensitivity analysis was performed on runoff coefficient using Vensim's™ Monte Carlo multivariate sensitivity analysis package to observe changes in discharge (Figure 18). The runoff coefficient for the model was set at .34 for corn area (ha). This coefficient was used because corn is a dominant land cover type in the catchment compared to other land use types. The minimum and maximum range was set to .01 to .99 for the analysis. Sensitivity results indicate that discharge is responsive to changes in the runoff coefficient constant as the highest discharge peaks are associated with the 95th and 100th percentiles.

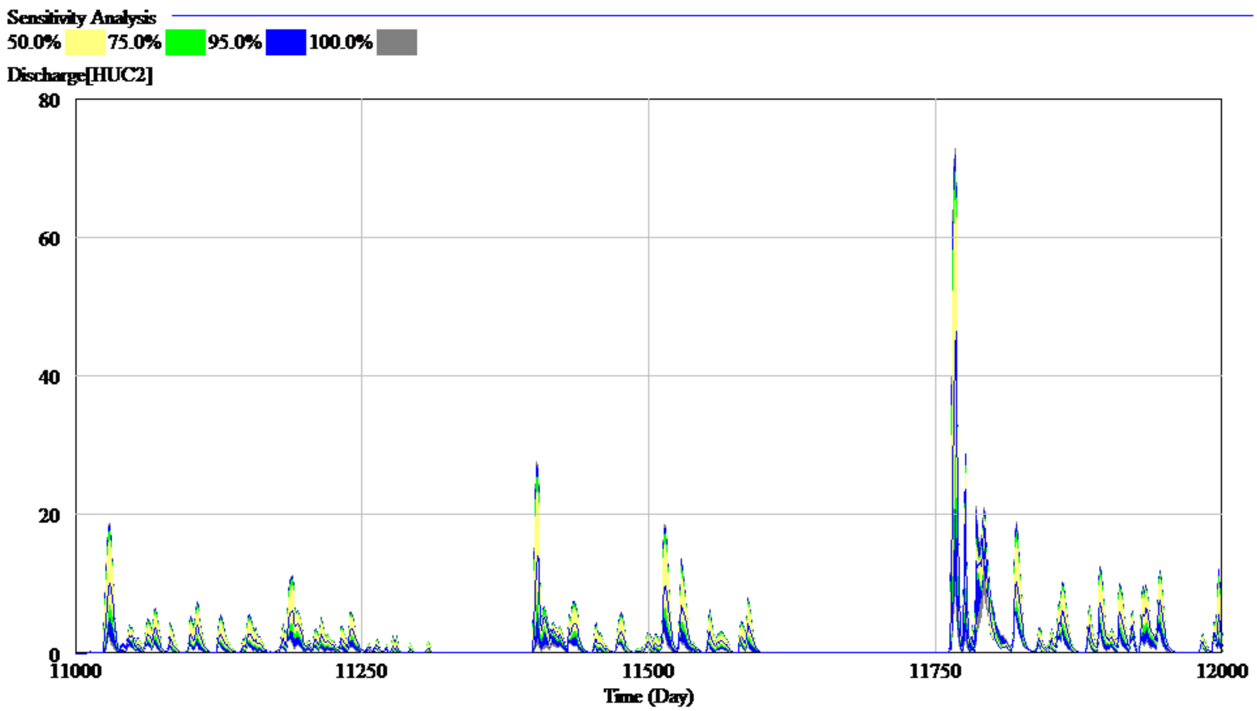

Figure 18. Sensitivity analysis of the runoff coefficient constant from February 1977 to November 1979 in the Skunk Creek water catchment (HUC10).

Extreme conditions tests were performed by increasing snowfall and precipitation inflows at the following rates 2,4,10, 20 and 100 (Figure 19). In all extreme condition tests discharge increased as expected. Groundwater was also checked and increased consistently across all variations of snow and precipitation. The behavior of the model remained characteristic of the physical boundaries and patterns expected for landscape scale hydrology.

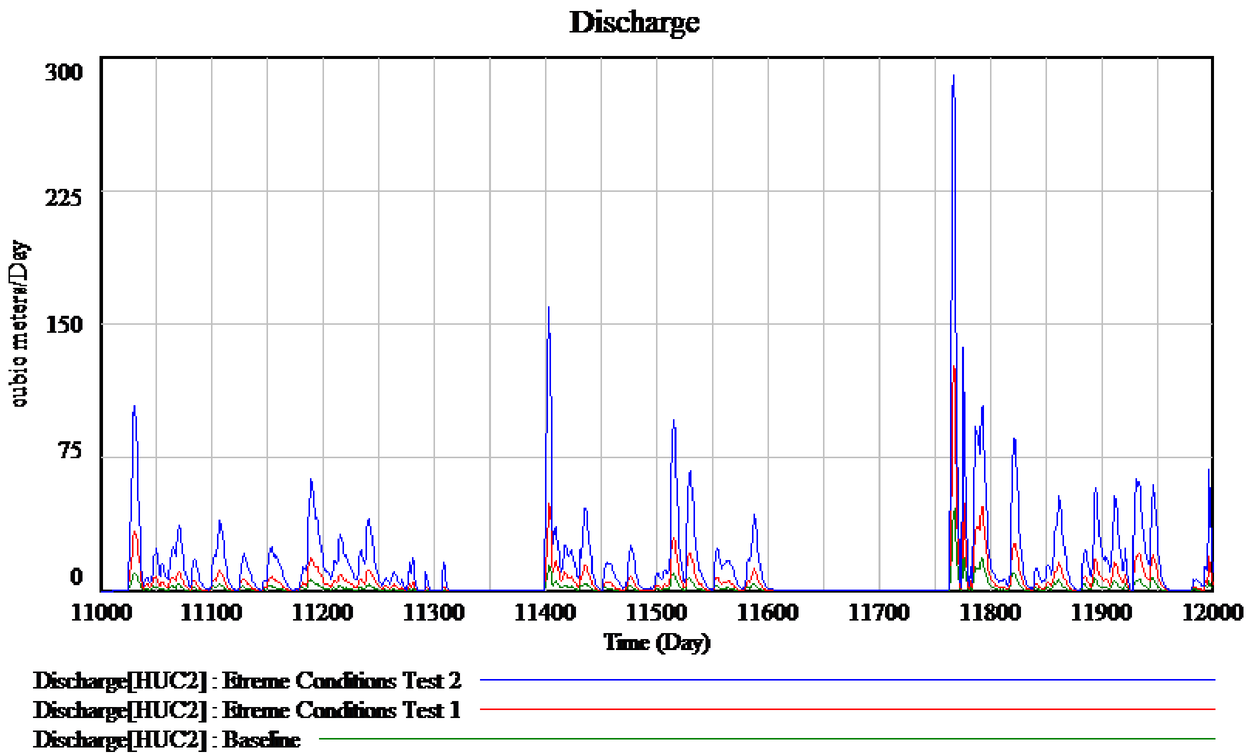

Figure 19. Extreme condition tests for discharge were done by altering snowfall and precipitation inflows and multiplying them times two and four, compared to the baseline simulation. The larger extreme conditions test (multiply times 10, 20, and 100) were omitted to maintain contrast.

5) Policy Design and Evaluation

Model Calibration. The model will continue to be calibrated and tested for the remaining areas in the BSR. Confidence in the model will allow us to forecast for erosion, water quantity and water quality under various scenarios. Turner et al. (2016) has developed forecasted rates of annual grassland conversion for probable economic, policy, and cultural scenarios which will be applied as our "what if" questions for the model. This proposed research will provide a more detailed quantitative evaluation of the potential environmental consequences of land use change in South Dakota, specifically forecasting soil erosion, water quantity, and water quality changes for the 50 years (2012-2062). Improved estimation of land use decisions and their externalities may help identify high-leverage, long-term solutions to mitigate environmental risk. South Dakota farmers, ranchers, and stakeholders will then have a new tool to evaluate land use decisions, identify possible strategies for long-term restoration and conservation, increase soil health, and improve water quality. This portion of methodological work is on-going. Initial policy results from model forecast will be presented at the conference session. Feedback of initial results of policy analysis will be used to further clarify and improve the model.

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APPENDIX

Key variables are reflective of the core structure of the dynamic hypothesis (DH) which represents the feedback processes that create (and perpetuate) the problem at hand. For example, total plant biomass is dependent upon the precipitation (i.e., endogenous), but precipitation is not dependent on any other variable within the system (i.e., exogenous). Several endogenous and exogenous variables influence soil erosion, hydrology and water quality changes and were tested within the model to capture the most representative structure of this problem (Table 1 and 2).

Table 1. Definitions of Key Endogenous Variables for Environmental Externalities.

Endogenous Variables	Definition
Farmland	Total land in crop production (ha/yr; Historic and Projected; Turner et al., 2016).
Grassland	Total land used for hay, pasture or fallow (ha/yr; Historic and Projected; Turner et al., 2016).
Total Plant Biomass	Total alive and dead above and below ground plant material throughout the growing season (kg/ha).
Disturbance	Index of anthropogenic impacts upon soil structure and health (disturbance impact).
Surface Water Runoff	Volume (m^3/s/yr).
Aggregate Sheet and Rill Erosion	Detached soil particles (tons/ha/yr).
Soil Organic Matter	Percent organic matter in the soil profile (%).
Soil Stability	Index of aggregate stability based management trends.

Table 1. Definitions of Key Endogenous Variables for Environmental Externalities (continued).

Best Management Practices (BMP)	Implementation of BMP's: No-till, Strip-till, Buffer Strips, Contour Strips, Livestock Integration, Cover Crops, etc. (annual effectiveness index).
Farmland Management	Index of soil disturbance from crop rotations, number of crop rotations per year, average bushels per acre.
Total Suspended Solids	Total soil particles in a stream or river (tons/ha-m/yr).
Regulations	Enforceable or scheduled mandates. An example may be a percentage of littoral or riparian cropland and pasture put into buffer strips to decrease sediment deposition and runoff velocity (ha).

Table 2. Definitions of Key Exogenous Variables for Environmental Externalities

Exogenous Variables	Definition
Projected Land Use	Farmland estimates for each LCC (Turner et al., 2016).
Climate	Precipitation (cm/day), temperature (daily average °C), and snow (daily average cm).
Technology	Specialized innovations that have altered production capabilities, e.g., a certain type of implement that did not previously exist (index of increased production).
Crop diversity and distribution	Diversity and distribution in planting based on predominant crops in the market (historical and future; spatially explicit-ha/yr).
Slope length and steepness factor	Hydrologic factor dependent on average slope length and steepness characteristic of each sub-basin (percent).
Soil properties	Soil texture, infiltration rate and organic matter.
BMP Policy Scenarios	Holistic and segmented impacts of BMP options that can be implemented (BMP annual effectiveness index).

c) Time Horizon

We have set time horizons for both model construction and model forecast that best represent the timeline of current and future grassland conversion in South Dakota. This model time horizon matches the extent of the historic data (1947-2011) and estimations of farmland (1,000 km^2/yr) change from 2012 to 2062 that were used in Turner et al. (2016). Time-series data will be aggregated for each delineated water-catchment for each metric (erosion, hydrologic and TSS). Likewise, the preceding study forecasted total conversion of LCC 1-8 grassland to cropland by 2062 (Turner et al. 2016); therefore, these previously established parameters of grassland conversion will be applied as our model's future behaviors (time horizon; present-2062) for each land use category.

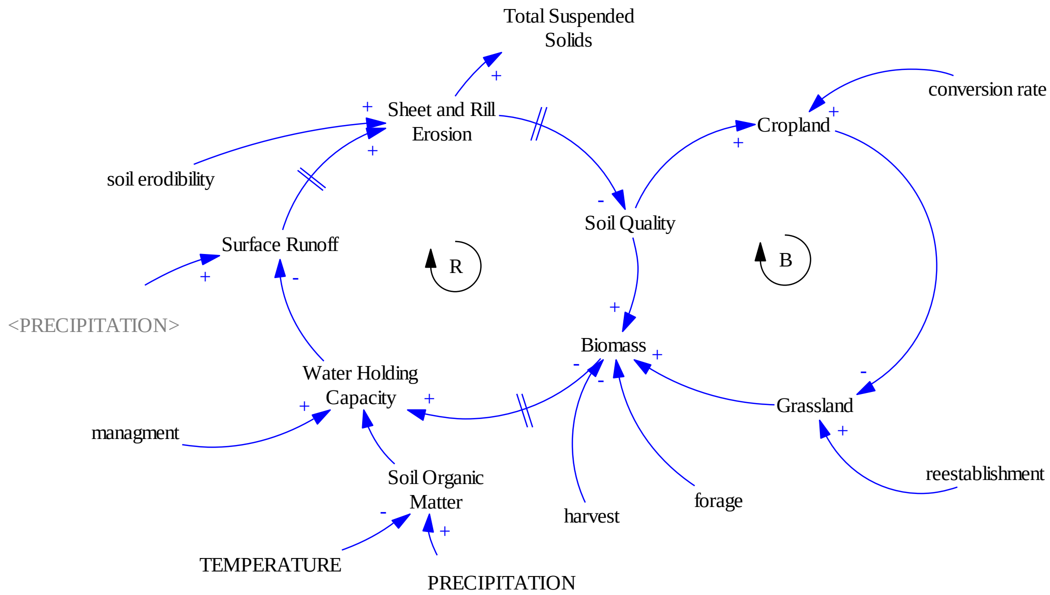

Figure 2. Dynamic Hypothesis Causal Loop Diagram.

Data Collection and Processing. Data collection and integration adhere to the previously established time horizon. Exogenous data were incorporated from a variety of sources and processed through multiple software packages (Excel™, Program R™, ArcGIS 10.3.1™ and Vensim™) to prepare for import into the SD model (Figure 3; see appendix Figures 5-8). Stream flow data were extracted from the United States Geologic Service (https://waterdata.usgs.gov /sd/nwis/rt) and climate data from the National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/data-access). Data were incorporated on a daily time-step and dt of 0.25.

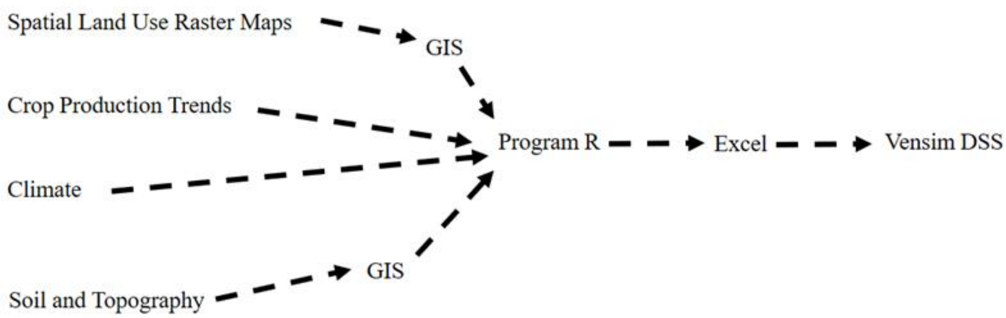

Figure 3. Conceptual diagram of processing data for Vensim™.

Table 3. System Dynamics Model Data (Turner, 2014; Chow et al., 1988).

Category	**Measurement**	**Unit**
Climate	Precipitation	cm/hr
	Temperature	C°
	Wind	m/s
	Land Cover	Hectares (ha) per Hydrologic Unit Code 10 (HUC)
	Management	Index
	Soil Factors	Infiltration rate (cm/hr)
	Land Capability Class	Range 1-8
	Crop and Grass growth	Total biomass (tons/ha)
Scenarios	Policy Scenarios	Farmland (1,000 km^2/yr)
Land	Slope	Length-m Steepness-percent
	Discharge	m^3/s

Spatial Land Use Raster Maps

Data were integrated from National Resource Conservation Service Spatial Gateway and United State Geological Survey- Earth Resource Observation and Science (i.e., annual land cover raster maps; https://datagateway.nrcs.usda.gov/; https://landcovermodeling.cr.usgs.gov/projects.php) to account for land cover changes from 1947 to 2012 (Sohl et al., 2012) at a spatial resolution of 250 X 250 m (approximately 6.25 ha). ArcGIS (version 10.1 and 10.1.3) was used to delineate spatial data to the HUC6 boundary of the Big Sioux River water catchment. A HUC stands for Hydrologic Unit Code, one HUC6 represents the entire BSR and HUC10s represent water catchments within the HUC6. Raster maps of the BSR annual land cover were processed via Program R using raster and polygon clipping techniques, which consequently improved data processing time instead of solely relying on ArcGIS. Raster maps were delineated from HUC6 to HUC10 and there are 53 unique HUC10s within the BSR (Figure 4)

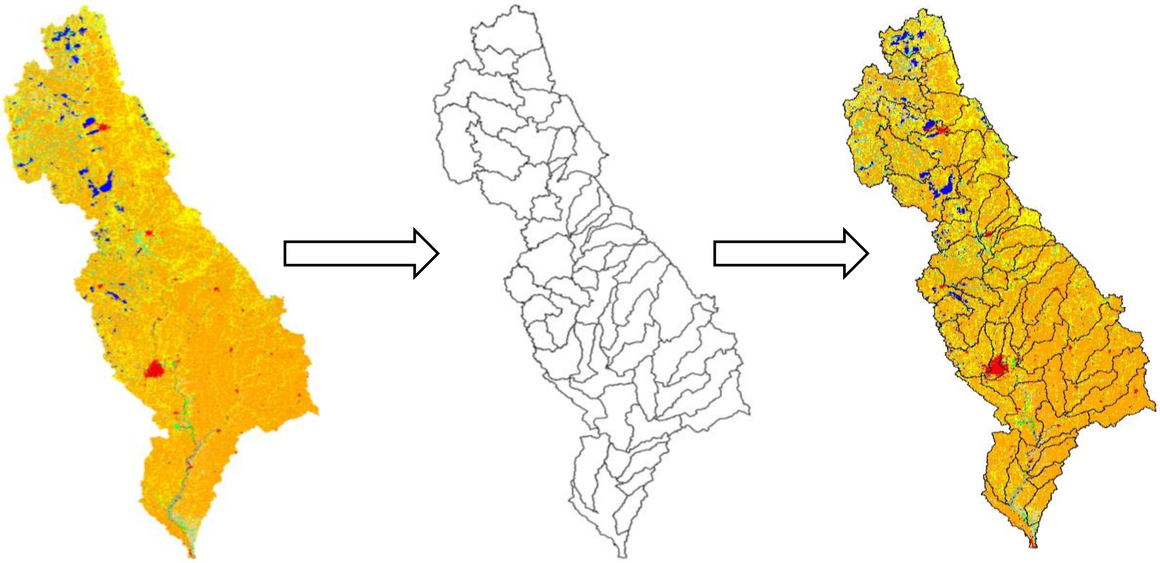

Figure 4. Raster clipped into the HUC6 BSR water catchment and then clipped into HUC10 BSR water catchments.

Spatial land use data contained unique pixel names: Open Water, Urban/Development, Mining, Barren, Deciduous Forest, Evergreen, Mixed Forest, Grassland, Shrub Land, Cultivated Cropland, Hay/Pasture, Herbaceous Wetland, and Woody Wetland. Pixels were then delineated into three categories Cultivated Cropland, Grassland, and All Other Land. Grassland and Hay/Pasture were categorized collectively as they typically share similar soils characteristics, topography, vegetation and are harvested by cattle or for hay at a similar frequency.

U.S. Agriculture Census data for specific crops per county were applied to each HUC10 (Figure 7). Crops included Corn (*Zea Maize*) Soybean (*Glycine max*), and Spring/Winter Wheat (*Triticum aestivum*; Figure 8). County lines may overlap multiple water catchments (HUC10s), counties that contained the largest area of each catchment were used for estimating annual corn, soybean, and wheat area (ha and km^2). Counties share typical crop production trends within the BSR which avoids large disparities between neighboring counties that overlap a HUC10 catchment (Figure 5).

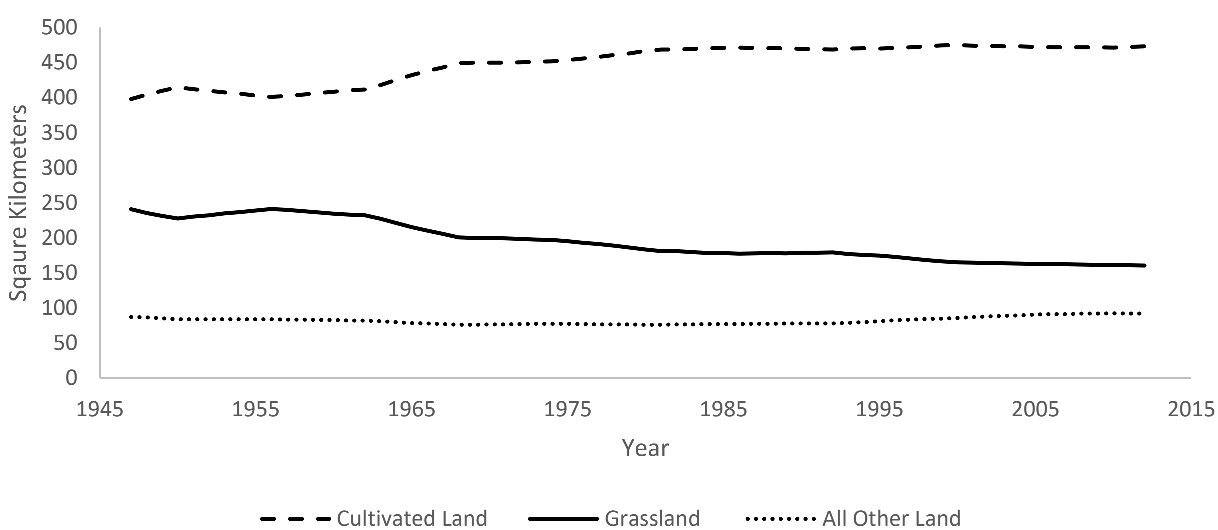

Figure 5. Cultivated Land and Grassland for a Union County (HUC10; approximately 724 km^2) from 1947-2012.

Crop area per catchment were calculated by the following formula:

$$\textit{Specific Crop Area}_i = \frac{\sum \textit{crop Areas}}{\textit{Crop Area}_i}$$

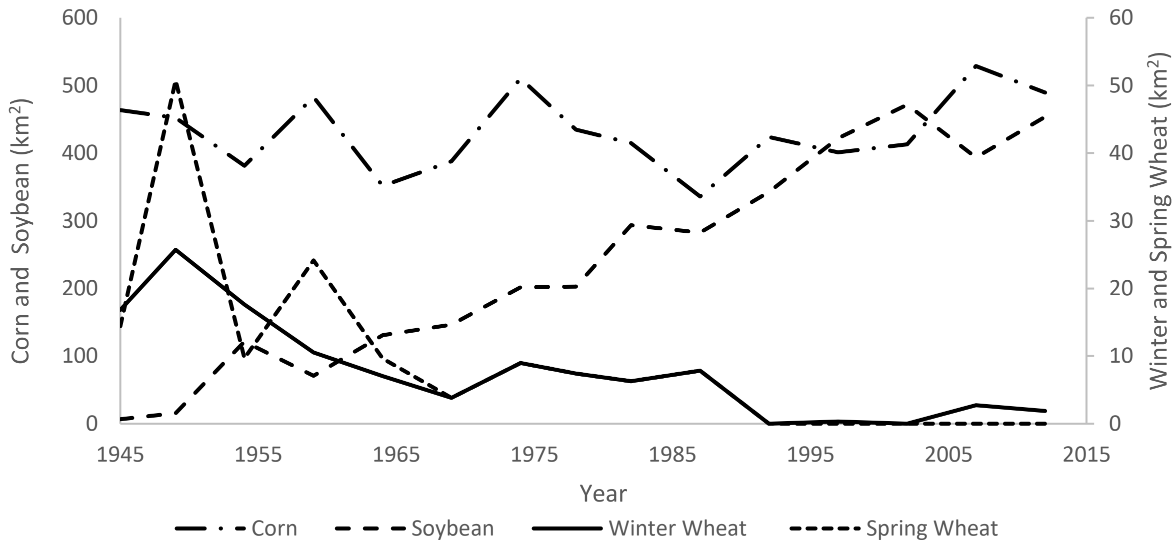

Figure 6. Corn, Soybean, Winter Wheat and Spring Wheat distribution for Union County 1945-2012. Trend based on USDA Agricultural Census data taken per county at five year intervals.

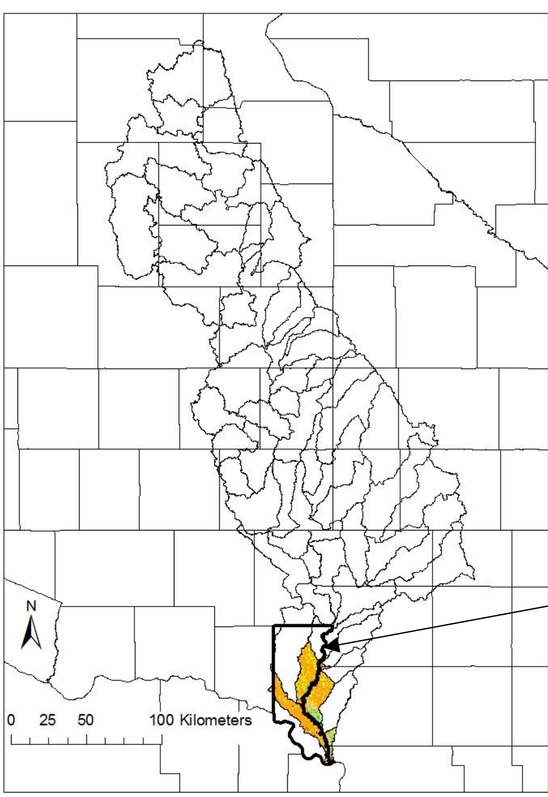

Figure 7. Union County, South Dakota crop trends (1947-2012) applied to the Big Ditch water catchment (HUC10) as the majority is within Union County.

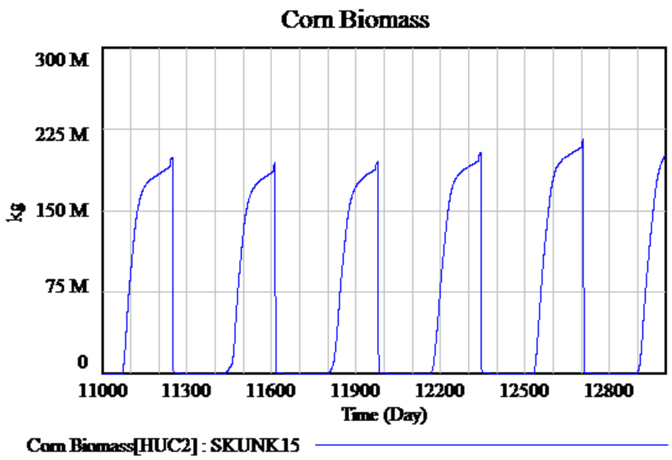

Figure 9. Skunk Creek water catchment (HUC10) corn biomass simulation.

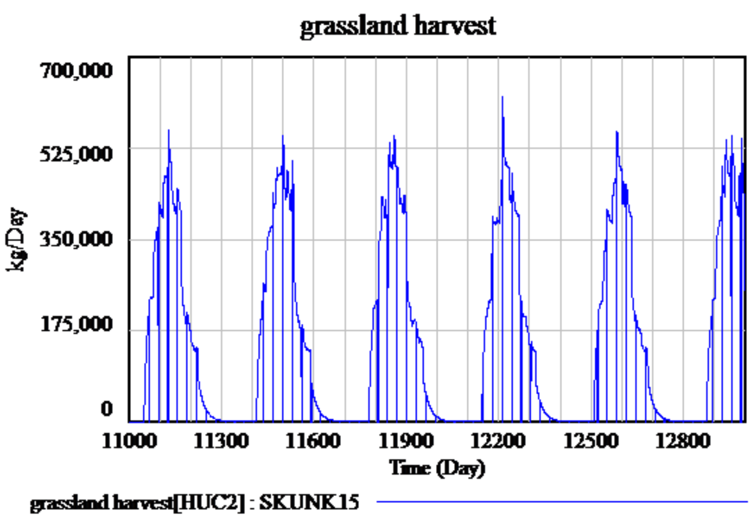

Figure 10. Skunk Creek water catchment (HUC10) grass harvest simulation.

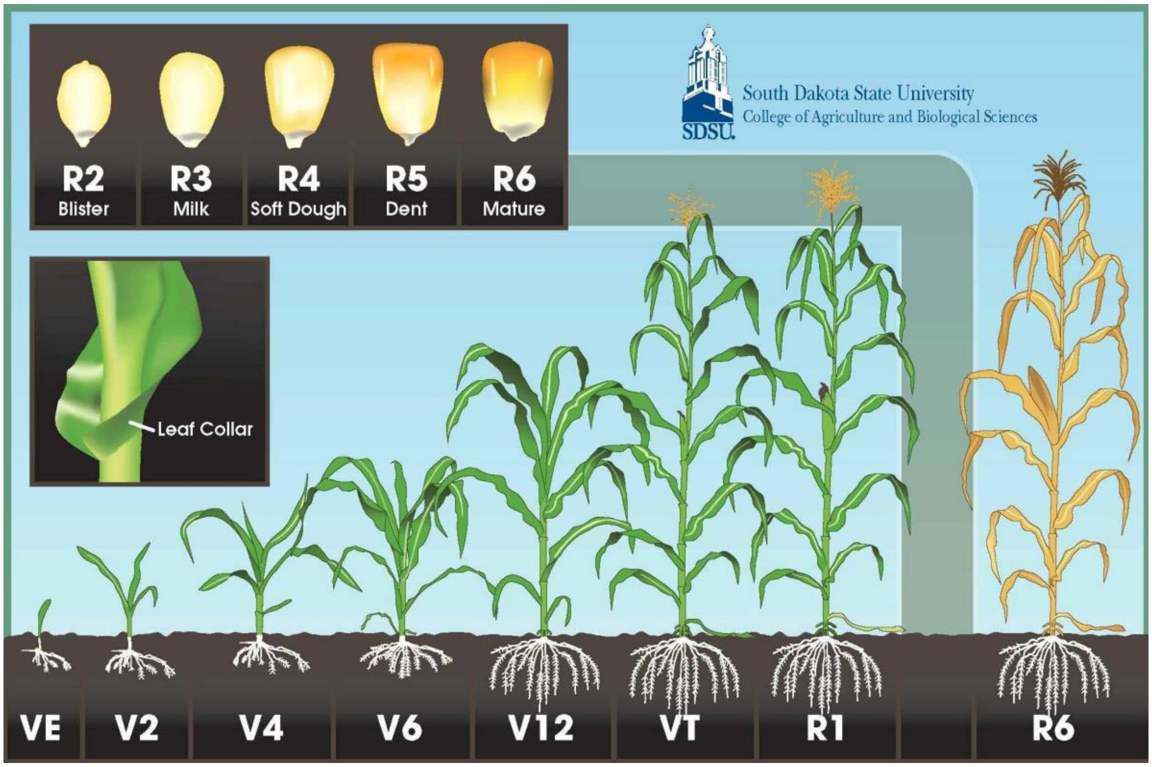

Figure 11. Corn growth stages (Thandiwe et al. 2016; Ritchie et al., 1993).

Table 4. Corn Growth Stages (Purdue University, 2009).

Vegetative Stages		Reproductive Stages	
Stage	Description	Stage	Description
VE	Emergence	R1	Silking - silks visible outside the husks
V1	One leaf with collar visible	R2	Blister - kernels are white and resemble a blister in shape
V2	Two leaves with collars visible	R3	Milk - kernels are yellow on the outside with a milky inner fluid
V(n)	(n) leaves with collars visible	R4	Dough - milky inner fluid thickens to a pasty consistency
VT	Last branch of tassel is completely visible	R5	Dent - nearly all kernels are denting
		R6	Physiological maturity - the black abscission layer has formed

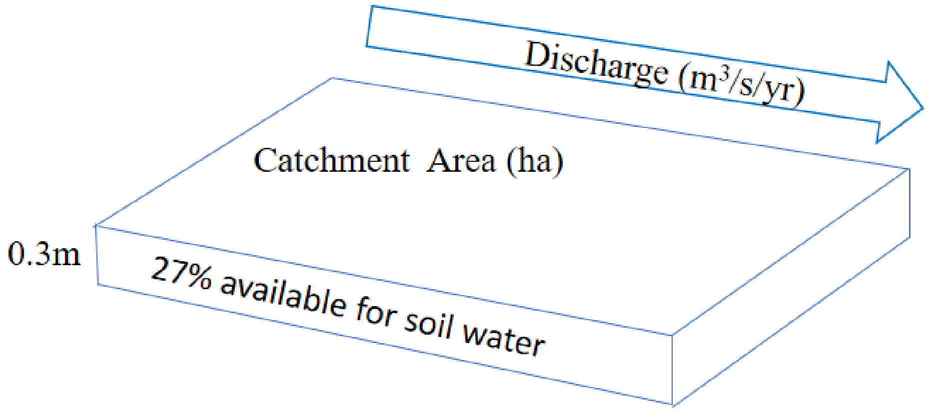

Figure 12. Soil water volumetric capacity and discharge.

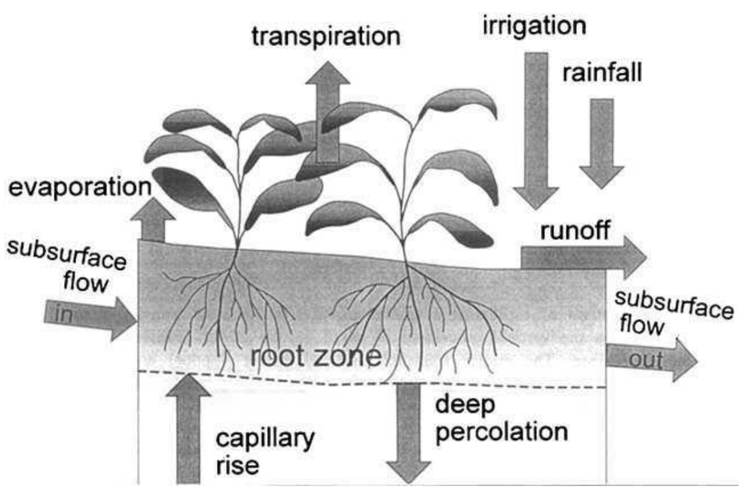

Figure 13. The hydrologic process (FAO, 2009).

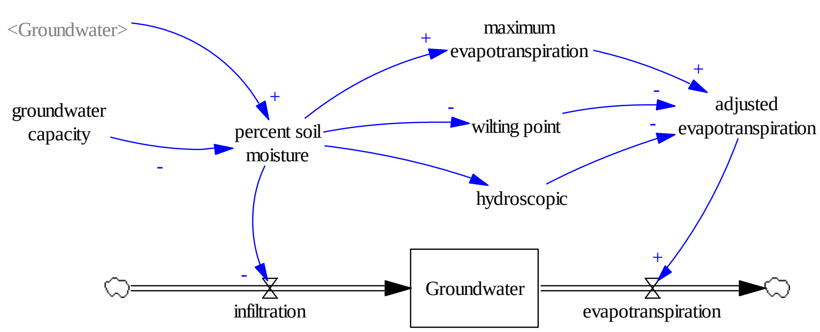

Figure 14. Soil moisture, infiltration, storage and evapotranspiration feedback loops.

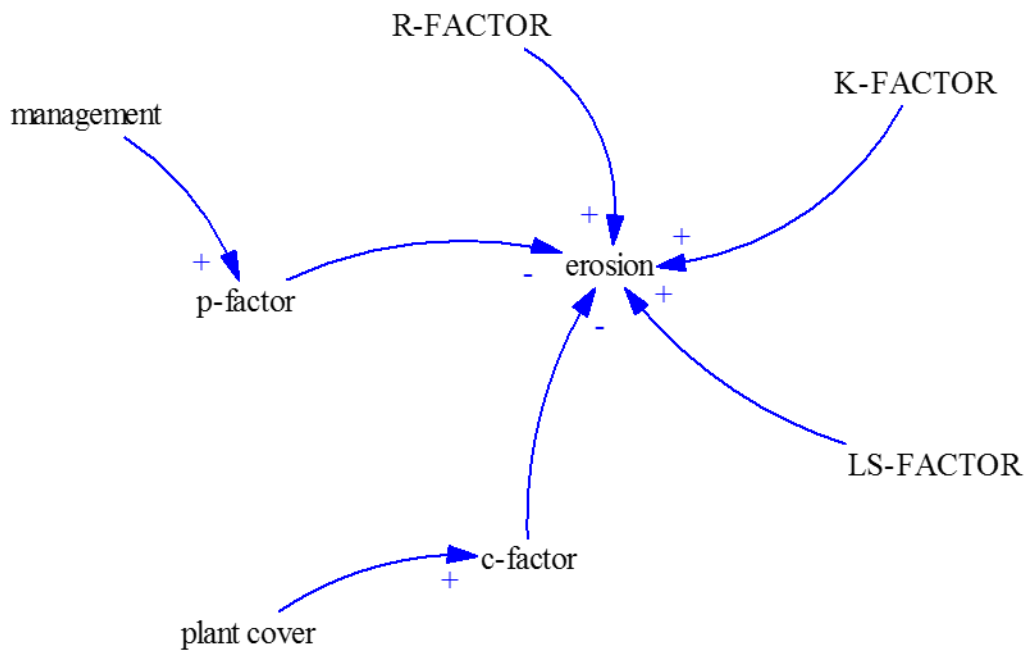

FIGURE 15. Revised Universal Soil Loss Equation integrated into the SD model and modified to capture daily cover and management impacts on aggregate rill and sheet erosion.

Rainfall erosivity (R) is estimated by multiplying storm energy (E) and precipitation intensity (I). Since mass in motion is proportional to velocity squared (Wischmeier and Smith, 1978), E can be computed using the following equation:

$$E = 916 + 311 \log_{10} I$$

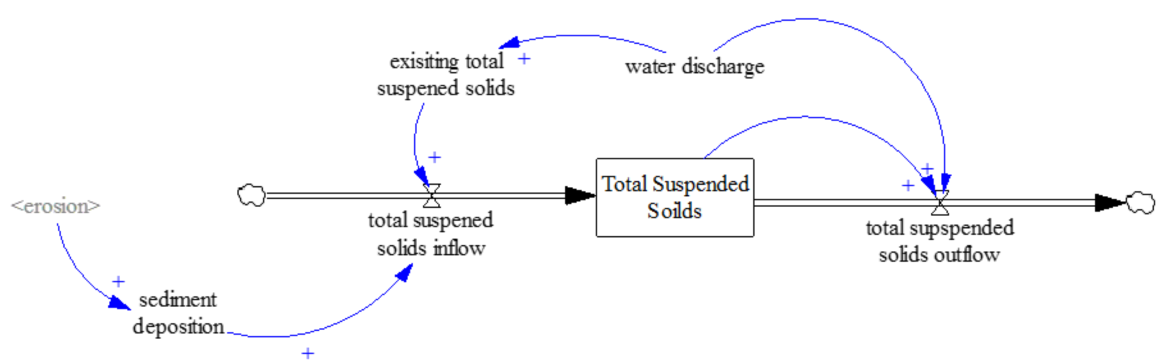

Figure 16. Total suspended solids dynamics incorporating typical TSS levels and additional sediment from erosion.