DELINEATION OF CRITICAL MANAGEMENT AREAS AT PLOT, FIELD, AND WATERSHED SCALES FOR CLAYPAN SOILS

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by

ASHISH MUDGAL

Drs. Claire Baffaut & Stephen H. Anderson, Dissertation Supervisors

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The undersigned, appointed by the Dean of the Graduate School, have examined the dissertation entitled

DELINEATION OF CRITICAL MANAGEMENT AREAS AT PLOT, FIELD, AND WATERSHED SCALES FOR CLAYPAN SOILS

Presented by

ASHISH MUDGAL

A candidate for the degree of

DOCTOR OF PHILOSPHY

and hereby certify that in their opinion it is worth of acceptance.

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Claire Baffaut (Chair)

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Stephen H. Anderson (Co-Chair)

____
E. John Sadler

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Allen L. Thompson

To My Grand Father

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Place: Columbia, MO

Date: (Ashish Mudgal)

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Abstract

Water and soil are two key elements for life on this planet, and improving and preserving their quality are of prime importance. Various human actions including use of intensive chemicals in agriculture have accelerated the deterioration of soil and water quality and given rise to non-point source pollutants. The claypan soil region of Missouri has a high runoff potential that increases the possibility of transport of non-point source pollutants to downstream sites. The present work was undertaken from plot to watershed scales to evaluate and present some solutions to these challenges. The present work was divided into five different studies, one a study of field measurements and the other four studies using model simulations.

The study 1 was undertaken to measure the impact of long-term agriculture on soil physical properties. This study was conducted to test the hypothesis that hydraulic properties for claypan soils can be significantly affected by long-term soil and crop management. Sampling was conducted during the summer of 2008 from two fields with Mexico silt loam (Vertic Epiaqualfs). One field has been under continuous row crop cultivation for over 100 years (Field) while the other field is a native prairie that has never been tilled (Tucker Prairie; TP). Values of coarse (60 to 1000 μm effective diam.) and fine mesoporosity (10 to 60 μm effective diam.) for the Field site (0.044 and 0.053 $m^3 m^{-3}$) were just above half those values from the TP site (0.081 and 0.086 $m^3 m^{-3}$). The

geometric mean value of saturated hydraulic conductivity (K_{sat}) was 57 times higher in the native prairie site (316 mm h^{-1}) than in the cropped field (5.55 mm h^{-1}) in the first 10 cm interval. The bulk density of the surface layer at the TP site (0.81 g cm^{-3}) was two-thirds of the value at the Field site (1.44 g cm^{-3}) and was significantly different throughout the soil profile except for the 20 to 30 cm depth.

The study 2 was conducted to identify the landscape positions that affect runoff and transport of pesticides in claypan soils. This simulation study evaluated the effects of variations in landscape position on runoff and dissolved atrazine utilizing a calibrated farm- and field-scale Agricultural Policy/Environmental eXtender (APEX) model. Twelve agricultural plots (18 x 189 m^2) in the Goodwater Creek watershed, a 7250 ha agricultural area in north-central Missouri, were simulated. APEX reasonably simulated runoff and dissolved atrazine concentrations with coefficients of determination (r^2) values ranging from 0.52 to 0.98 and 0.52 to 0.97, and Nash-Sutcliffe efficiency (NSE) values ranging from 0.46 to 0.94 and 0.45 to 0.86. Simulated results indicated that the runoff and the atrazine load at the plot outlet increased when the backslope length increased while keeping the steepness constant. The maximum simulated runoff among different sequences of landscape positions occurred when the backslope position was located adjacent to the outlet.

The study 3 was scaling up of the results from Study 2 to the field scale. The objective of this study was to develop a physically-based index to identify Critical Management Areas (CMAs) in a 32-ha field. The field was characterized by a claypan, a restrictive clay layer occurring within the upper 30 to 50 cm, and was under a corn (*Zea mays*) - soybean (*Glycine max*) crop rotation since 1991. Thirty-five subareas were defined based on slope, claypan depth, and soil mapping units. The Agricultural Policy/Environmental eXtender (APEX) model was calibrated and validated from 1993 to 2002 for runoff, sediment, and atrazine loads. Simulated output by subarea was correlated with physical parameters including claypan depth (CD), surface saturated hydraulic conductivity (Ksat) and subarea slope (SL). Two indices were developed, the Conductivity Claypan Index (CCI; CD*Ksat /SL), and the Claypan Index (CPI; CD/SL) that correlated with runoff (r = -0.77), and atrazine and sediment loads (r = -0.55). These indices captured 100% of CMAs based on runoff and sediment yield and 75% of CMAs because of atrazine load, as predicted by APEX. These critical areas were also areas with lower productivity. Management scenarios were simulated that differentiated the management of the CMAs from the rest of the field.

In study 4 we used simulation models to estimate the impact of long-term agriculture on surface runoff, sediment yield, atrazine load, and corn and soybean yields. A calibrated and validated APEX (Agricultural Policy Environmental eXtender) model for the 32 ha field was utilized to simulate the impact of long-term agriculture on selected model outputs. Soil samples collected during Studies 1 and 2 were used to represent post- (Field 1) and pre-agricultural scenarios (TP). The APEX model was run for thirty years (1978 to 2007) for the pre- and post-cultivation scenarios with a corn-soybean crop rotation and mulch tillage management. The selected model outputs were compared on an annual time scale to analyze the impact of long-term agriculture. There was a significant increase in annual average atrazine load (82%), and reductions in corn (39%) and soybean (75%) yields for the post cultivation scenario. These results show that the improvement of soil properties on agricultural lands would be beneficial not only to enhance crop yields but also to reduce non-point source pollutants.

The study 5 was conducted to delineate critical management areas (CMAs) in the Goodwater Creek Experimental Watershed (GCEW), also characterized by claypan soils, to simulate effects of placement of best management practices (BMPs) in these CMAs. Two indices, CCI and CPI, were used to delineate CMAs in the watershed. Twenty-five % of the total watershed area under agricultural land use except pasture had the lowest values of CCI and CPI which were treated as CMAs. The SWAT model satisfactorily calibrated and validated for streamflow, sediment yield, phosphorus load, and atrazine load for the GCEW, and was used to confirm the CMAs delineated by indices. The coefficients of correlation (*r*) found between selected annual average model outputs generated from different parts of the watershed and the index values for those areas indicated significant relationships. Significant correlations were found for both indices with surface runoff, lateral flow, sediment yield, and sorbed nutrients generated from those areas. Furthermore, if the model outputs were broken down by management practices, the *r* values became stronger. CMAs had higher number of days with water and nutrient stresses that correlated well with the indices. Therefore, the indices CPI and CCI in conjunction with knowledge of current management practices could be an easy and less costly and time consuming method to delineate CMAs in watersheds with claypan soils. To reduce the runoff and non-point source pollutants, these delineated CMAs were targeted with BMPs: filter strips (FS), grassed waterways (GWW), and terraces; and after installation of BMPs the thirty year model simulations showed significant reductions in simulated sediment yields (51 to 54%) and phosphorus loads (19 to 23%). Targeting CMAs with BMPs delineated using the CCI and CPI indices can be an effective way to reduce the sediment and phosphorus loads from the GCEW.

CHAPTER 1

INTRODUCTION

The United States has made immense advances in the last three decades to meet water quality standards relative to point source pollution from industry and sewage treatment plants. Efforts have been conducted to meet specific concentrations for selected water quality measures relative to specific water uses (USEPA, 1979). In contrast, more work is needed to control pollution from diffuse or non-point sources (Braden and Segerson, 1993; Carpenter et al., 1998). Consequently, non-point source (NPS) pollution remains a significant challenge for the nation for improving water quality.

Current efforts include soil and water conservation programs to help accomplish the objective of reducing NPS pollution. In 2003, a multi-agency effort known as the Conservation Effects Assessment Project (CEAP) was started by USDA-Natural Resources Conservation Service (NRCS), USDA-Agriculture Research Service (ARS), and the USDA-Cooperative State Research, Education, and Extension Service (CSREES) to assess past efforts and program effectiveness in reducing NPS pollutants and maintaining an economical, ecological and environmental balance (Duriancik et al., 2008). Conservation practices that have received emphasis in CEAP are conservation buffers; erosion control; wetland conservation and restoration; establishment of wildlife habitat; and management of grazing land, tillage, irrigation water, nutrients, pesticides and pests (Batie et al., 2006). This variety of practices have different impacts in diverse environments, NPS pollutants are released from various sources, and the variability occurs both because of sources as well as human activities.

To study the cumulative impacts of multitude of activities, a common geographic area is needed, typically an area that drains into a common stream, lake, or recharge area or overlays ground water. This type of approach is called a watershed-scale approach; a watershed being defined as the total land area from which water drains into a particular stream or river. Using a watershed-scale approach, a collective effort is put together involving stakeholders' knowledge and desires, scientific data, and tools and techniques in a recursive fashion so that the ideas and solutions developed could be used elsewhere for a holistic improvement of the watershed.

But individual watersheds have variable hydrology because of variations in topography, soils, parent materials, climate, and different land uses over time. Crop management practices also contribute to spatial heterogeneity, beyond that attributable to natural processes (Cambardella and Karlen, 1999; Jung et al., 2006). Therefore, environmental problems may occur when uniform management practices are superimposed on variable soil-landscapes or on the whole watershed (Fuller, 2001).

In any watershed, some areas generate disproportionate amount of runoff and pollutants (Agnew et al., 2006). These areas may be termed as Critical Management Areas (CMAs). Identifying CMAs is one of the current challenges for controlling NPS pollution, because these areas require management that reduces generation and transportation of NPS. Once these areas are identified in the watershed, their associated risks can be controlled with site-specific management using the best and most economical management practices available for the particular remediation (Norris, 1993). CMAs based on geographical location, soil type, land use, and management have specific parameters that could set these areas apart from others.

CMAs are comparative sites within the watershed that are generating higher amounts of runoff and NPS pollutants; therefore, the types of parameters and values for the parameters responsible for producing runoff and NPS pollutants would be watershed specific. There are many parameters that differentiate one location from another; landscape position could be used as a surrogate for initial differentiation. The landscape plays an important role in the watershed in terms of soil, surface and subsurface hydrology and subsequently in runoff, NPS pollutant transport, and crop yield. Landscape topography affects soil physical and chemical properties usually through prior erosion and deposition processes (Ebeid et al., 1995; Delin et al., 2000; Iqbal et al., 2005). Changes in the landscape, which are reflected by changes in soil properties (King et al., 1983; Wilding, 1985; Kreznor et al., 1989; Moore et al., 1991; Odeh et al., 1991), among the major variables that can be used in identifying critical areas of the watershed.

Once CMAs are delineated, they may be investigated by using two different approaches; one includes monitoring the different landscapes and the other uses simulation models. The first approach is very labor intensive and time consuming, and thus expensive. Advances in distributed hydrologic modeling have given rise to the development of improved tools that are capable of simulating physical, chemical and biochemical processes that control the transport of contaminants in watersheds (Manguerra and Engel, 1998). Simulation models are the tools used for the comprehensive study of all processes because of their ability to relate causes (inputs) to effects (outputs) and to predict the effects of improved management practices at the watershed outlet. Continuous time step physical process simulation models were developed in the 1970’s to provide insight in the long-term impacts of agricultural practices on water quality.

Based on the extent of area simulated by these models, they are often divided into field-scale and watershed-scale models (Srivastava et al., 2007). Field-scale models provide estimates of pollutant loading at the edge of field while simulating processes that are spatially distributed, whereas watershed-scale models route flow and pollutants from the fields through stream channels to the watershed outlet (Gassman et al., 2009). Watershed-scale models are required at large scales and for river basin planning and management, which require the understanding of multiple processes including relative water demand and use, surface and groundwater availability, and the impacts on the water cycle and balance. Watershed-scale models typically require less site-specific information than do field-scale models, and by-and-large provide less site-specific information. Whereas, field-scale models use more site-specific information and hence tend to simulate more detailed and smaller-scale features. Thus, field-scale models are best suited for studies where local effects of variation in soil properties and landscape position are to be considered.

Field-scale models include finer scale information of physical and chemical soil properties, topographic features, management practices, and hydrologic processes. Therefore these models are better suited for the estimation of parameters used to identify CMAs. The output parameter information estimated by finer scale models can then be extrapolated at larger watershed scales for similar areas.

Simulation models are highly sensitive to soil hydraulic properties (White and Chaubey, 2007; Feyereisen et al., 2007), and these properties are highly variable even within in the same soil series based on their management (Rachman et al., 2004; Seobi et al., 2005; Skaggs et al., 2006). Therefore, parameter estimation at finer scales for delineating CMAs by using simulation models should also be accompanied with field measurements of various soil and topographic features. Once the soil and topographic properties are measured for different management, the model may be adjusted accordingly to better represent the actual processes.

Study Background

At the watershed scale, many studies have shown no or very little reduction in NPS pollutants (Park et al., 1994; Inamdar et al., 2002; Simpson and Weammert, 2008; Meals et al., 2010), even after incorporation of different management practices. Among reasons for these findings, one could be the implementation of best management practices (BMP) in less critical areas or employing inappropriate BMPs. Therefore, identification of CMAs is of utmost importance and accurate identification of proper CMA parameters have to be recognized. Once CMAs are identified, an assessment needs to be conducted using different BMPs so the appropriate BMP is selected and the maximum benefits are realized from BMP incorporation.

Some soils in the mid-western region of the US are characterized by a claypan. Claypan soils are defined by a thick layer of clay approximately 15 to 45 cm below the surface and having much higher clay content than the overlying material. Claypan soils impart a unique hydrology by impeding the vertical flow of water and thus increasing surface runoff and associated non-point source pollutants; these soils also influence the spatial variability in crop yields (Kitchen et al., 1999; Jung et al., 2005; Myers et al., 2007). In claypan soils, many researchers have established that the depth of the claypan plays an important role in local hydrology (Kitchen et al., 2005; Jiang et al., 2007; Myers et al., 2007). Studies have found that the depth to the claypan could be a good indicator of CMAs (Kitchen et al., 2005; Lerch et al., 2005) in claypan regions. Fraisse et al. (2001), studying claypan soils, found that, apart from clay depth, the elevation or the upland slope also plays an important role in controlling local hydrology and subsequently the crop productivity. Other than these properties, soil hydraulic properties often are important parameters controlling surface and subsurface flow (Nyberg, 1995; Rachman et al., 2004; Rocha et al., 2006). If these hydraulic properties can distinguish critical from non-critical areas, they along with slope and depth to clay could provide insight for the delineation of CMAs in claypan regions.

As discussed, the initial set of parameters impacting the generation of runoff and NPS pollutants along with crop yield could be studied by using a field scale model at small scales like plots and fields. The Agricultural Policy Environmental eXtender (APEX) is a one such field-scale daily time step model. The APEX model uses weather, soil property, land use, and topography data to simulate water balance and water quality processes, and can be used to evaluate various land management strategies including sustainable practices and erosion control practices to assess pollutant transport. The model also includes flow and pollutant routing through streams as in watershed-scale models (Gassman et. al., 2010). The field-scale APEX model has many advantages since field units can be represented by the model with their spatial relationships so that various field sections can be routed in a specified order, with their simulated multiple cropping systems, and with their physical BMPs such as filter strips, terraces, buffers, etc. Once the relationships between sensitive parameters and CMAs are developed, they can be used at bigger scales for the delineation of CMAs and subsequently providing information on where to locate BMPs to have the maximum impact for NPS pollutant reduction.

At the watershed scale, a continuous daily time step model may be used for the evaluation of the effects of BMP implementation on NPS pollutant loadings. A river basin or watershed-scale model developed by Dr. Jeff Arnold for the USDA- ARS is the Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2002a). SWAT was developed to predict the impact of land management practices on non-point source pollutant loading for larger-scale watersheds with diverse soils, land use and management conditions over long periods of time (Neitsch et al., 2002b).

Keeping in mind the above discussion, the approach in the present study has been to determine the sensitive parameters for the delineation of CMAs at plot and field scales using the APEX simulation model, and extrapolate these results at the watershed scale by using the larger-scale SWAT model. Field studies have also been conducted to measure soil properties as inputs for the models to assess the impact of land management on soil hydraulic properties.

Objectives

The main objectives of this study were to identify parameters for the delineation of CMAs where BMPs should be implemented in priority for maximum impact on NPS pollutant reduction.

Study 1. This study was entitled “Effects of long-term soil and crop management on soil hydraulic properties for claypan soils”. Specific objectives of the study were to measure and compare soil hydraulic properties including soil water retention, pore size distributions, bulk density, and saturated hydraulic conductivity for a field under row crop cultivation for over 100 years and for a native prairie that has never been tilled.

Study 2. This study was entitled “APEX model assessment of variable landscapes on surface and dissolved herbicides”. The specific objectives of the study were to test whether APEX is sensitive to variations of soil properties because of landscape position, and to determine the effects of the sequence and size of landscape positions with their corresponding slope and soil properties on the amount and intensity of simulated runoff and dissolved atrazine losses from claypan soils.

Study 3. This study was entitled “Estimation of parameters for the delineation of critical management areas using the simulation model APEX in claypan soils”. The specific objectives of the study were to determine the correlation between soil and topographic parameters with generated runoff, sediment yields, atrazine loads and crop yields and use these correlations to delineate CMAs. Furthermore, implementation of different BMPs was assessed in minimizing runoff, sediment yield, and atrazine loads.

Study 4. This study was entitled “Assessing the impact of long-term cultivation on runoff, sediment yield, atrazine load, and crop yield from claypan soils using the simulation model APEX”. The specific objective of the study was to compare the amount of runoff, sediment yields and atrazine loads generated from a field prior to cultivation and after 100 years of cultivation.

Study 5. This study was entitled "Delineation of critical management areas in the Goodwater Creek Watershed using two indices". The specific objectives of the study were to delineate critical areas using two indices developed from soil properties and topography and assess placement of BMPs in these delineated areas on reductions in runoff, sediment yields and atrazine loads using the simulation model SWAT.

All five studies were written independently in the format of journal manuscripts for publication purposes.

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CHAPTER 2

LITERATURE REVIEW

Critical Management Areas

During the twentieth century, efforts in the agricultural community were aimed at improving the productive potential of available land resources using selected agri-chemicals. These attempts have lead to serious deterioration of the environment from soil erosion, damaging levels of non-point source pollutants and sometimes reductions in productivity. Therefore improved management systems are required not only to enhance productivity but also to minimize the detrimental impacts on the environment. Experimental studies coupled with simulation modeling may be a way to develop efficient management systems (Ahuja et al., 2000).

In any geographical unit, there are areas that are more critical for production and environmental impact relative to others (Tripathi et al., 2003; Dickinson et al., 1990; Storm et al., 1988; Maas et al., 1985). These areas may have relatively lower agricultural productivity, higher runoff generation potential, and higher generation of non-point source pollutants (Agnew et al., 2006); therefore, these areas are termed as Critical Management Areas (CMA). Identifying critical areas has been a widely accepted option for not only controlling higher runoff and non-point source pollutants, but also to increase productivity per unit land area (White et al., 2009; Gitau et al., 2004). Once critical areas are identified in the watershed, their associated risks can be controlled with site-specific management using the best and most economical practices available for particular remediation (Gburek et al., 2002; Norris, 1993).

The delineation of CMAs should be based on easily available and physically measured parameters, so that they are readily comprehensible to local land managers, farmers and stake holders (White et al., 2009). Such parameters may include soil topography, soil properties, upstream area, soil and crop management, etc. Parameters important for delineation of CMAs are location specific and are dependent on the local hydrology and agricultural practices and affected by climate.

Walter et al., (2000) had found CMAs in the New York water supply watershed as flat areas, particularly at the base of hill slopes. These areas were characterized by excessive lateral flow because upstream steep slopes have high infiltration capacity and a restrictive layer; as a result there was little runoff from these slopes but significant subsurface flow. As a result, the bottom flat areas became prone to saturation because of incoming subsurface flow and thus to runoff generation. The major runoff process was saturation excess flow (Hewlett and HIbbert, 1967).

Delineation of CMAs is also dependent on the spatial scale of the geographical unit under consideration. Spatial scale in increasing order could be from plot to field to watershed. As the size of the considered unit increases, the accuracy of parameters required for CMA delineation reduces; therefore strategies for delineation of CMAs should also be based on scale.

Plot Scale Studies At the plot scale, variations in landscape position may be a good criteria for CMA delineation. Landscapes can be defined by slope gradient, slope length, slope curvature, as well as regularity of knolls and depressions. A landscape position could be a single entity if the parameters stated above are similar and the landscape exhibits homogeneity for specific properties and processes. Different landscape positions affect soil properties, hydrology, and other related processes (Ruhe, 1956). Ruhe (1960) proposed the landscape elements as summit, shoulder, backslope, footslope and toeslope, and these elements widely are used with minor modifications for soil studies, agricultural management, and mitigation of non-point source pollutants (Hall and Olson, 1991). Separating plots into these five basic elements (summit, shoulder, backslope, footslope and toeslope) is a logical approach to relate soil properties and landscapes, as it minimizes the variation in soils and dependent processes within a single landscape section. Hence, distinct values of soil properties can be assigned to each section to study their impact on runoff and non-point source pollutants (Ovalles and Collins, 1986). Pachepsky et al. (2001) concluded that even gentle slopes (slope gradient < 5%) showed substantial differences in soil textures, which lead to the variability in water retention at different landscape positions.

Milne (1936a, b) was among the initial researchers to share in the idea that soils are uniquely related to landscape position when he introduced the concept of catena. It was suggested, that processes at one point on the landscape not only affect that position but also the soils on other parts of the landscape. Soil differences are because of drainage conditions, differential transport of eroded material, and leaching, translocation and deposition (Milne, 1936a).

King et al. (1983) found that, while soil distribution varied as a function of landscape position, slope length and slope gradient, the most significant factor controlling soil distribution was the shape of the slope. Geomorphologic positions and topographic attributes such as elevation, slope, aspect, and hydrologic and erosion processes, influence the depth of horizons and soil properties (Moore et al., 1991; Odeh et al., 1991).

(Wilding, 1985) found that the least variable soil properties were soil color (hue and value), pH, and the thickness of the A horizon while the most variable soil properties were the thickness of the B horizon, and solum depth. Kreznor et al. (1989) also reported that the thickness of A and B horizons were correlated with landscape position.

Jiang et al. (2007a) measured soil hydraulic properties, which included saturated hydraulic conductivity (K_{sat}), soil bulk density, pore size distribution, and soil water retention, for claypan soils in central Missouri at different landscape positions and for selected crop management and soil depths. They found the backslope had significantly lower K_{sat} values (3.4 mm h^{-1}) in comparison to the summit (15.9 mm h^{-1}) and footslope (19.7 mm h^{-1}) landscape positions. Similarly, soil bulk density, pore size distribution, and soil water retention were different for each landscape position.

A study by Brunner et al. (2004) using the Water Erosion Prediction Project (WEPP) model to determine the impact of spatial distribution of soil types on hillslope soil loss, showed that soils at the summit position had a thick solum because of stable soil formation on a flat surface, whereas soils at the shoulder position had shallow A horizons because of active erosion processes. Valley and footslope soils showed hydromorphic features and accumulation of soil material from upslope. Simulations considering a catenary soil sequence showed a clear spatial demarcation between erosion and sedimentation zones, which was verified by soil investigations. One of the outcomes of the study was that simulations including a higher number of soil-landscape units generated a more realistic spatial distribution of erosion–sedimentation processes for hillslopes.

Gabbard et al. (1998) studied the influence of topographic properties and hydrologic processes on runoff and soil erosion occurring at specific landscape positions by simulating the runoff and soil loss in the laboratory. They found there was an increased probability of more soil loss as they moved from summit to lower backslope. Naef et al. (2002) experimentally evaluated various landscape positions according to the type and characteristics of the dominant runoff process. They then proposed cropping systems and management practices specifically adapted to each area.

Field Scale Studies Determining various properties at a field scale in different landscapes would be costly and more time consuming in comparison to plot scales. Instead, smaller order soil surveys are commonly used approaches to classify soils at a higher resolution (Trangmar et al., 1985). These surveys generate regions with different soil classes, while designating average values of soil properties for the defined mapping unit (Webster, 1985). A surrogate approach is used to actually predict the soil properties for the majority portion of the region, where the actual measurements have not been done (Cambardella et al., 1994). Often, correlations can be developed between easily measured properties and the more complex and cumbersome to measure properties.

Minasny (2007) provided a list of soil properties predicted using various predictor variables by different authors (Table 2.1). He used the term pedotransfer function introduced by Bouma (1989) meaning “data we have into what we need”, using basic soil properties to estimate difficult and expensive soil properties.

Table 2. 1 Examples of pedotransfer functions (after Minasny, 2007).

Predicted Soil Properties	Predictor Variables	Authors
infiltration rate after certain period	initial water content, moisture deficit, total porosity, non-capillary porosity, hydraulic conductivity	Canarache et al. (1968)
soil thermal conductivity	texture, organic matter content, water content	De Vries (1966)
bulk density	particle size distribution	Rawls (1983)
gas diffusivity	air-filled porosity at -10 kPa	Moldrup et al. (2000)
soil mechanical resistance	organic carbon content, clay content, bulk density	Mirreh and Ketcheson (1972)
soil shrinkage curve	clay content	Crescimanno and Provenzano (1999)
volumetric shrinkage, liquid limit, plastic limit, plasticity index	organic matter content, clay content, CEC	Mbagwu and Abeh (1998)
degree of over consolidation	bulk density, void ratio	McBride and Joose (1996)
rate of structural change	organic matter content, clay content, pH	Rasiah and Kay (1994)
soil erodibility factor	geometric mean particle-size, clay and organic matter content	Torri et al. (1997)
cation exchange capacity (CEC)	clay content, organic matter content	Curtin and Rostad (1997)
critical P level, P buffer coefficient	clay content	Cox (1994); Chen et al. (1997)
soil organic matter	soil color	Fernandez et al. (1988)
P sorption	pH in NaF	Gilkes and Hughes (1994)
pH buffering capacity	organic matter content, clay content	Curtin and Rostad (1997)
nitrogen-mineralization parameters	CEC, total N, organic carbon content, silt and clay content	Rasiah (1995)
Phosphorous (P) adsorption	clay content, pH, soil color	Sheinost and Schwertmann (1995)

Once certain properties impacting generation of runoff, non-point source pollutants and crop yield are predicted for defined mapping units, the spatial variation in these properties can be used for the delineation of CMAs at the field scale. Fraisse et al. (2001) in the claypan region of Missouri, identified management zones using elevation, slope, and soil ECa (apparent soil electrical conductivity) data and the variability of crop yield in an agricultural field; they found that elevation and soil ECa data better represented the crop yield variability in the field. Kitchen et al. (2005) in a different study confirmed their findings that a field with claypan soils could be better divided into different management zones for better crop yield by using elevation and soil ECa data. They developed productivity zones from the continuous spatially measured crop yield data and found productivity zones delineated using elevation and soil ECa data better agreed with the previously developed productivity zones.

Soil ECa data were found to be correlated with many physical and chemical soil properties impacting the hydrologic cycle in the field and consequently influencing runoff and non-point source pollutant generation as well as crop yield (McNeill, 1992; Lund et al., 2001; Sudduth et al., 2005). Jiang et al. (2007b) found a good correlation between upper and lower limit of plant available water and ECa for claypan soil landscapes in the U.S. Midwest region. The r^2 values between inverse of ECa and profile plant available water (PAW) were found to be 0.67 and 0.87 for two different fields in the study area.

There have been other indexes developed for delineation of CMAs to study the hydrologic behavior of specific locations. One that has been extensively used is the Topographic Wetness Index (TWI; Beven and Kirkby, 1979) and its many modified versions (Hjerdt et al., 2004; Ibbitt and Woods, 2004; Sorensen et al., 2005; Grabs et al., 2009).

$$TWI = \ln(As/\tan\beta) \quad (1)$$

where, As is the specific catchment area and β is the slope gradient. TWI was previously used by Fraisse et al. (2001) in Missouri at the location of the present study for identifying management zones. These authors compared the variability of TWI, elevation, slope, and soil ECa (apparent soil electrical conductivity) as well as the variability of crop yields in an agricultural field and found that elevation and soil ECa better represent the crop yield variability in the field than TWI. Kitchen et al. (2005) confirmed their findings and concluded that productivity zones developed from the field's measured crop yield maps agreed with the management zones delineated using elevation and soil ECa data.

Watershed Scale Studies At the watershed scale, availability and accuracy of necessary data for the delineation of CMAs is further reduced. Renschler et al. (2002) compared various techniques for estimating elevation data to be used for topographic analysis at the watershed scale. They found that as the cost for determining elevation data increases these data become more beneficial and accurate. In their comparison, they found the topographic data provided by the U.S. Geological Survey was satisfactory in estimating the upslope drainage area and delineations of channel networks and watershed boundaries.

Bingner and Theurer (2001) used two different Digital Elevation Models (DEM) for estimating the topographic factors and found that with 0.1 and 1.0 m vertical resolution DEM captured and delineated similar areas critical for soil erosion. At this larger scale, data accumulation is not the only problem but also the monitoring of various undetected sinks and sources of pollutants. These sinks and sources lead to a gap between field estimated efficiency of management practices in the reduction of pollutants, and these reductions being undetected at the watershed level (Sharpley et al., 2008).

Simulation models are one of the tools used for the estimation of pollutant loads in a watershed and also for delineating CMAs. Srinivasan et al. (2005) compared two models, SWAT (Soil Water Assessment Tool) and a physically based model Soil Moisture Distribution and Routing (SMDR) for delineating critical source areas (similar to CMAs) for runoff generation and phosphorus transport. They found these models had the capability for simulating spatial data representing runoff generation at the watershed scale. However, neither model could simulate the interactions between the runoff generating areas and all runoff generated was assumed to reach the stream.

Endreny and Wood (2003) used an Export Coefficient Model (ECM) coupled with geographic information system (GIS) raster maps to delineate phosphorus critical loading areas in New York's West Branch Delaware River Watershed. A Contributing Area and Dispersal Area (CADA) weighting function was developed for predicting spatial patterns of phosphorous loadings; the CADA weighting function was based on landscape position, runon from upslope areas, and availability of trapping opportunities. They successfully classified these areas into three parts: 1) areas where pollutants were present, 2) areas vulnerable to pollutant transport with runoff, and 3) areas with likelihood of trapping pollutants using buffers. The resulting critical management areas generally matched what was observed in the field.

Veith et al. (2004) have tried a different approach for targeting CMAs; they used an optimization process using a genetic algorithm (GA) to determine the optimal location of practices to meet pollution reduction requirements with minimum cost. They applied the optimization strategy in an agricultural watershed in Virginia and found that this methodology was able to achieve similar reductions in sediment loads at a lower cost by using a ‘targeting the critical area approach’. On the other hand GA techniques have limited scope because they need more technical expertise, more resources, and complex estimations.

Busteed et al. (2009) used the SWAT model to target critical source areas generating higher amounts of sediment and phosphorous loads in the Wister Lake Basin, Oklahoma. They found that just 10% of the basin was generating 85% of the total pollution. Therefore, they were able to target specific agricultural producers and enroll them in their water quality program, thus optimizing limited cost share funds.

Hydrologic Simulation Modeling

Simulation modeling is an integral part of human planning efforts among diverse disciplines; models are used to understand and visualize the functions and outcomes of different systems. Modeling is a vital tool to assist with better planning, management and understanding of processes, especially in fields which encompass long-term impacts and interrelationships among different components and processes. Agriculture row crop production is one such area which is governed by complex interactions among the atmosphere, plants, soil, and water.

There have been plenty of simulation models developed in the past four decades for simulating various processes associated with agriculture. Srivastava et al. (2007)

reviewed many of the commonly used models for predicting non-point source pollutant transport. They divided the models based on their spatial scales, i.e. plot, field, and watershed scale models. They concluded that with the advent of increased computing power, models could be used with more confidence and for more diverse applications for better management of agriculture and subsequently for improved environmental quality.

Early simulation models were often focused on single events using the unit hydrograph method which estimated runoff, water routing, and sediment yield (Gassman et al., 2009). Later, models were developed for daily time step continuous simulation. Many components of these models use previously developed technologies, adapted for daily time step simulation. For example, the estimation of runoff from a rainfall event can use the NRCS (Natural Resources Conservation Service) curve number technique (U.S. Department of Agriculture-NRCS, 2004). The major benefit of using this method is the ease of use and minimal amount of input data required. Other methods include calculation of infiltration amount mainly by the Green and Ampt equation (Green and Ampt, 1911); however, this equation needs rainfall data at an hourly time scale. Many models also use water flow equations such as the Richards, Darcy and/or Hooghoudt equations (Refsgaard and Storm, 1995; Bingner and Theurer, 2003) along with a water balance to estimate the amount of runoff from single events.

Advances in distributed hydrologic modeling have given rise to the development of improved tools which are capable of simulating physical, chemical and biochemical processes that control the transport of contaminants in watersheds, estimate components of the hydrologic cycle, and predict crop productivity (Manguerra and Engel, 1998). Simulation models allow the comprehensive study of all processes because of their ability to relate causes (inputs) to effects (outputs) and to predict effects of management practices at the watershed outlet. Various simulation studies have been conducted to estimate runoff, pollutant loadings and crop yields at field and watershed scales (Arabi et al., 2006; Brunner et al., 2004; Harman et al., 2004; Saleh et al., 2000)

Based on the areal extent simulated, these models are often divided into field-scale and watershed-scale models (Srivastava et al., 2007). Field-scale models provide estimates of pollutant loading at the edges of field while considering spatial distribution of processes (Williams et al., 2008), whereas watershed-scale models route flow and pollutants in/from fields through stream channels to the watershed outlet. Responses from watershed-scale models are required at a large scale for river basin planning and management, which requires an understanding of multiple processes including relative water demand and use, surface and groundwater availability, and the impacts on the water cycle and balance. Watershed-scale models typically require less site-specific information than do field-scale models, and by and large provide less site-specific information (Neitsch et al., 2002a). Whereas, field-scale models use more site-specific information and hence tend to simulate more detailed and smaller-scale features. Thus, field-scale models are best suited for studies where local effects of variation in soil properties and landscape position are to be considered.

One of the field/watershed scale models is the Agricultural Policy/Environmental eXtender (APEX) model (Williams et al., 2000). APEX is an intermediate between the field and watershed scales and can be used to evaluate various land management strategies by simulating sustainability, erosion, water balance and quality, soil quality, plant competition, weather and other management practices at the edge of field. APEX also includes flow and pollutant routing through streams as with watershed scale models (Sharpley and Williams, 1990; Williams et al., 1995; Saleh et al., 2000; Wang et al., 2006 and 2007). In APEX, field units can be represented by the model with their spatial relationships so that various field sections can be routed in a specified order, with multiple cropping systems and also with physical structural management practices such as filter strips, terraces, buffers, etc.

A continuous daily time step model, for a river basin or watershed scale model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS) is the Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2002a). SWAT was developed to predict the impact of land management practices on non-point source pollutant transport in bigger scale watersheds with diverse soils, land use and management conditions over long periods of time (Neitsch et al., 2002b).

One major advantage of modeling is the efficient simulation of various management strategies without excessive investment of time or financial resources. Therefore, after simulating smaller scale complexities with a field scale model (APEX) and getting more insight into the hydrologic processes, the APEX model output can be routed to a watershed scale model for a holistic evaluation of the effects of soil and water conservation practices on a larger scale. Saleh et al. (2000), Osei et al. (2000), Gassman et al. (2001), and Saleh and Gallego (2007) have reported on studies which have taken advantage of this approach by using the field scale model APEX and routing its output to the watershed scale model SWAT.

Wang et al. (2007) used the APEX model for nine forested watersheds in East Texas of areas ranging from 2.58 ha to 2.74 ha. They simulated flow, sediments, organic

N, and organic P. Out of nine watersheds, one was control and the others had different levels of clear cutting. The model APEX was able to simulate the effects of clear cutting, and there was a significant increase in streamflow, sediments, organic N, and organic P from the control watershed to the other eight watersheds.

A comprehensive understanding of any simulation model is essential before applying the model to any specific project in different geographical regions. Borah and Bera (2004) extensively reviewed eleven different watershed scale models: AGNPS (AGricultural Non-Point Source Pollution Model), AnnAGNPS (Annualized AGricultural Non-Point Source Pollution Model), ANSWERS (Areal Non point Source Watershed Environment Response Simulation), ANSWERS-Continuous, CASC2D (CASCade 2 Dimensional), DWSM (Dynamic Watershed Simulation Model), HSPF (Hydrological Simulation Program—Fortran), KINEROS (Kinematic Runoff and Erosion model), MIKE SHE (MIKE System Hydrologic European), PRMS (Precipitation-Runoff Modeling System), and SWAT. The evaluation of these models was based on the calculation procedures used by the different models for simulation, especially for agricultural watersheds. They concluded that SWAT is a capable model for continuous hydrologic and non-point source pollution simulation in agricultural watersheds. SWAT was also found to be effective for evaluating the effects of BMP.

Every model needs to be calibrated initially; however, this can create modeler bias towards model outputs, and hence different predictions can be developed by separate individuals with the same model. Sometimes models are developed for some particular geographical location or for a specific use. Hence, they should not be used for other uses or for different geographical locations which can provide erroneous predictions. To minimize modeler bias, a general protocol should be followed for model selection to calibration, simulations, and output interpretations. A model use protocol has been developed by USEPA and details have been discussed by Engel et al. (2007).

Krause et al. (2005) discussed nine different efficiency criteria for testing the calibration of simulation models. The major objectives of efficiency criteria are to assess the agreement between simulated and measured data. In distributed models where calibration of one output affects others, a multi-variable technique should be used. It was recommended that using a combination of efficiency criteria would be the best approach. Various statistical methods have been used to evaluate the model's goodness of fit such as the linear regression (r^2) method, Nash and Sutcliffe (1970) efficiency (NSE), and percent bias (Pbias). These criteria have been extensively used in modeling studies (Ramanarayanan et al., 1997; Santhi et al., 2001; Wang et al., 2007), and are explained in detail by Krause et al. (2005) and Moriasi et.al. (2007). Many researchers have considered various acceptable ranges for r^2, NSE, and Pbias based upon the amount of available measured data, output time interval, and purpose of the study. Moriasi et al. (2007) provided acceptable ranges for NSE and Pbias when quantifying the accuracy of monthly simulations of watershed runoff and pollutant loadings.

Efforts are increasing over the years to reduce water quality deterioration, hence more precise studies are required to achieve this objective. Using the Water Erosion Prediction Project (WEPP) model, Brunner et al. (2004) concluded that simulations including a higher number of soil landscape units generate a more realistic spatial distribution of erosion–sedimentation processes for hillslopes.

Harman et al. (2004) studied various management practices and runoff control structures for reducing atrazine losses using the simulation model APEX. The most efficient practices they found were: construction of sediment ponds, grass filter strips, banding a 25% rate of atrazine, and constructing wetlands. Because of these practices, reductions in atrazine concentrations at the watershed outlet were up to 45%. Other options for reducing atrazine losses including alternative tillage practices and split applications were less efficient.

Gassman et al. (2006) performed a simulation study for 30 years to determine the environmental and economic benefits of different structural and management practices. They found that most practices were able to reduce surface runoff, sediment loads, and nutrient loads. Economic model simulations showed that the cost of sediment reduction was from $6 to $65 per hectare based on management or structural practices. But, they concluded the best results were achieved when different combinations of practices were applied.

Inamdar (2006) presented the major challenges in simulating hydrologic and water quality processes in riparian zones. The major emphasis was on more spatial characterization, that is, to simulate specific processes at landscape scales rather than selecting a suitable time period for simulation. Model selection also plays an important role; models should not be too complex such that huge input data are needed for simulation.

Best management practices are recommended based on expert judgment to reduce non-point source (NPS) pollutant loads. Srivastava et al. (2003) designed an algorithm for designing BMP placement to optimize NPS reductions with minimum investment. They linked the optimization algorithm with an NPS model (AnnAGNPS), and simulated five years of output with different BMPs. The BMPs selected from their optimization algorithm were able to reduce NPS loads significantly with the least amount of investment.

Soil Hydraulic Properties

Soil hydraulic properties are of major importance for managing agriculture in sustainable and environmentally responsible ways. These properties not only influence plant growth but also the transport of non-point source pollutants (Puckett et al., 1985)

Soil hydraulic properties are dynamic and are affected by many factors. These factors include soil structure (Fuentes et al., 2004), biological plants and organisms which grow and decay (Beven and Germann, 1982; Meek et al., 1992), shrink-swell cracks in clay soils (Baer and Anderson, 1995), and agricultural activities such as tillage and traffic compaction (Udawatta et al., 2008; Fuentes et al., 2004). Erosion is also an important process because it can degrade soil physical properties (Lal and Moldenhauer, 1987; Arriaga and Lowery, 2003).

Seobi et al. (2005) found soil under perennial grass and tree buffers had lower bulk density and higher porosity than soil under row crop areas. They also concluded that after six years of establishing buffers, soil under buffers can store more water and hence would have lower runoff and less sediment, nutrient, and herbicide losses. Similarly, Rachman et al. (2004) showed that areas under perennial grass hedges for more than ten years had lower bulk density and clay content and higher porosity and saturated hydraulic conductivity than areas under row crop cultivation for the same soil. Skaggs et al. (2006) studied the effects of forest management on saturated hydraulic conductivity (K_{sat}) and found K_{sat} values for a mature plantation forest were 20 to 30 times higher than values given in the soil survey for the study area. They attributed this deviation in K_{sat} values to the difference in land management.

Jiang et al. (2007a) examined the impact of four conservation management systems, mulch till, no-till, CRP (Conservation Resource Program) and perennial hay, on soil hydraulic properties influenced by landscape position on claypan soils. They found that most of the effects of management were limited to the top 10 cm of soil. Below this depth, soil hydraulic properties were more dependent on the depth from the surface to the claypan. At the backslope position, which had the shallowest depth to claypan, they found the lowest K_{sat} in comparison to summit and footslope positions. They concluded that among these four management systems, the use of perennial grasses improved soil hydraulic properties the most.

The above studies showed the impact of short-term land management on soil hydraulic properties. Udawatta et al. (2008) compared soil hydraulic properties between native prairie (NP), restored prairie (RP), conservation reserve program (CRP), and plots under a corn-soybean rotation (CS). They used computed tomography images and found number of pores, number of macropores (>1000 μm diam.), macroporosity, mesoporosity (200-1000 μm diam.), and fractal dimensions were significantly higher for NP, RP, and CRP than for CS treatments. They also measured K_{sat} and soil bulk density; it was found that the CS treatment had the lowest K_{sat} value and the highest soil bulk density of the treatments. They concluded the restored prairie had improved soil hydraulic properties compared to the CS treatment, but they were still inferior to the NP treatment.

Similar findings were confirmed by Fuentes et al. (2004) at a different study site; they compared hydraulic conductivity and soil water characteristics among native prairie (NP), soil under conventional till (CT), and soil under no-till (NT). They found hydraulic conductivity was significantly higher for NP than the CT and NT treatments. The top soil layer for NT had higher K_{sat} than the CT but near saturated hydraulic conductivity values were similar for both treatments. They concluded that, even after thirty years of NT treatment, soil properties were still different than NP but were improved in comparison to the CT treatment.

While management can affect soil properties through soil compaction and root processes, long-term management can have additional effects because of erosion and loss of the topsoil layer. Soil erosion critically reduces plant production when a topsoil silt loam layer becomes thinner and a subsoil high in clay content is exposed (Larson et al., 1983; Pierce et al., 1983; Scrivner et al., 1985). This is a typical feature of soils in Major Land Resource Area 113, Central Claypan Area, where an argillic horizon high in clay content (> 50%) is overlaid by silt loam (Blanco-Canqui et al., 2002; Lerch et al., 2005). Removal of the silt loam layer through erosion exposes the high clay content layer; Pierce et al. (1983) found that erosion of these types of soils disproportionately reduces crop productivity.

Murphy et al. (1993) measured hydraulic conductivity and sorptivity at 10-and 40-mm tension. They compared the temporal variation in these properties from two fields under wheat crop with two different cultivation systems, direct drilling and traditional tillage. The soil properties were found to be highly variable during the growing season. Tillage, plant growth, rainfall and wetted soil compaction were major contributors toward this temporal variability. The soil with traditional tillage prior to sowing, together with stubble burning, had lower values of hydraulic properties at 10-mm tension than the soil with direct drilling.

Soil and Water Quality in Claypan Soils

Good quality water and soil are critical for sustainable agricultural production. However, various agricultural inputs can pollute water resources if improperly used. Runoff and soil erosion are two hydrologic processes potentially responsible for deterioration in water and soil quality. Soil erosion is one of the main causes for the loss of nutrient-rich topsoil and a decline in soil fertility in agricultural lands (Syers, 1998; Stoorvogel and Smaling, 1998; Lal, 1999).

Soils that naturally have a significant runoff component because of low permeability, such as claypans or steep slopes, are especially susceptible to herbicide losses in runoff (Ghidey et al., 2005). Lerch et al. (2005) assessed the long-term surface and ground water quality and also long-term changes in soil quality in a 36-ha field in northeastern Missouri. They found topsoil loss, and hence decreased depth to the claypan from historic erosion of the field, was a key soil quality indicator. Spatial variability in soil loss over the last 150-200 years controls soil quality, water quality, and crop productivity patterns. In claypan soils, soil erosion has led to the loss of topsoil and therefore exposure of low hydraulic conductivity clay soils with high potential of runoff generation and subsequently non-point source pollutant loads and simultaneously reduced crop yields.

Determination of the variability of agrichemical application amounts along with soil properties is an important interrelation to efficiently manage fertilizer and herbicide inputs. The adsorption behavior of herbicides is related to soil properties such as organic matter (OM), CEC (cation exchange capacity) and soil pH (Sheets, 1970; Weber, 1970; Ghidey et al., 1997; Hager et al., 1999). Sudduth et al. (1994) reported significant within field variability among areas in soil nutrient levels, water holding capacity, soil pH, top soil depth, crop growth, and yield for fields and plots located in claypan soil regions. Further, Ghidey et al. (1997) showed that in the same claypan soil areas, spatial variability of OM, CEC, and soil pH have significant effects on the spatial and temporal variability of herbicide concentrations in runoff.

Kitchen et al. (2005), in a study on claypan soils, found that crop yield is highly variable and could be better represented by topography and clay depth as measured using an electrical conductivity sensor than with an Order 1 Soil Survey. They found that plant available water was related to the clay depth and was a main factor affecting the crop yield because of seasonal variation. Areas with shallow clay depth (< 30 cm) were found to have low yields because of less availability of water to crops.

Blanchard and Donald (1997) estimated the contamination of groundwater beneath claypan soils. They sampled groundwater wells from 1991 to 1996 four times a year. Atrazine and alachlor were found in only 7.2 and 0.4 % of samples. Therefore herbicide leaching was limited in claypan soils. They also concluded the amount of herbicides found in groundwater was more dependent upon local hydrology than the application amount.

In claypan soils, surface water is vulnerable to contamination instead of groundwater, therefore studies in claypan soils should place more emphasis on surface water problems rather than groundwater. Ghidey et al. (2010) evaluated plot-scale exponential models to calculate atrazine and metolachlor concentrations as a function of application rate, runoff volume and days after application; they then expanded these relationships to the field scale. They confirmed the models developed were able to predict herbicide losses especially atrazine at the field scale. They also concluded in claypan soils, no-till management has higher concentrations and losses of atrazine than mulch till management.

Claypan soils also have shrink-swell potential (Baer and Anderson, 1995) that further complicates the hydrology of landscapes with soils high in smectitic clays. Due to cracking, water percolates rapidly to the groundwater; this seasonal cracking of the soil matrix results in poor estimation of runoff and infiltration because of the changing soil storage conditions (Arnold et al., 2005). Water quality concerns in claypan soils are dominated by transport of non-point source pollutants with surface runoff. Therefore, in claypan soils, reduction in surface runoff and associated dissolved pollutants should be of major emphasis.

Making use of past studies evaluating claypan soils can assist with delineation of CMAs. This requires starting at smaller scales for enhanced understanding of the hydrology, and processes for the generation and transport of NPS. Once these processes are considered at smaller scales, results may be scaled up to field and watershed scales. After CMA delineation, these areas can be targeted for BMP placement in order to have maximum reduction in runoff and NPS at downstream water bodies. The literature reviewed also implies that targeting of CMAs in claypan soils may also enhance economic returns from grain crop production systems, thus providing environmental as well as economical benefits. Therefore, a detailed study is needed to evaluate methods for delineating CMAs and testing appropriate placement of BMPs in claypan soil landscapes to improve utilization of resources with maximum returns.

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CHAPTER 3

EFFECTS OF LONG-TERM SOIL AND CROP MANAGEMENT ON SOIL HYDRAULIC PROPERTIES FOR CLAYPAN SOILS

Abstract

Many land management decisions are based on local soil properties. These soil properties include average values from soil characterization for each soil series. In reality, these properties might be variable because of substantially different management, even for similar soil series. This study was conducted to test the hypothesis that for claypan soils, hydraulic properties can be significantly affected by long-term soil and crop management. Sampling was conducted during the summer of 2008 from two fields with Mexico silt loam (Vertic Epiaqualfs). One field has been under continuous row crop cultivation for over 100 years (Field) while the other field is a native prairie that has never been tilled (Tucker Prairie; TP). Soil cores (76 x 76 mm [(3.0 x 3.0 in)]) from six replicate locations from each field were sampled to a 60 cm (24 in) depth at 10 cm (3.9 in) intervals. Samples were analyzed for bulk density, saturated hydraulic conductivity (K_{sat}), soil water retention, and pore size distributions. Values of coarse (60 to 1000 μm [(0.0024 to 0.039 in)] effective diam.) and fine mesoporosity (10 to 60 μm [(0.00039 to 0.0024 in)] effective diam.) for the Field site (0.044 and 0.053 $m^3\ m^{-3}$ [(0.044 and 0.053 $in^3\ in^{-3}$)]) were just over half those values from the TP site (0.081 and 0.086 $m^3\ m^{-3}$ [(0.081 and 0.086 $in^3\ in^{-3}$)]). The geometric mean value of K_{sat} was 57 times higher in the native prairie site (316 mm h^{-1} [(12.4 in h^{-1})]) than in the cropped field (5.55 mm h^{-1} [(0.219 in h^{-1})]) for the first 10 cm (3.9 in) interval. Differences in K_{sat} values were partly

explained by the significant differences in pore size distributions. The bulk density of the surface layer at the TP site (0.81 g cm^{-3} [(50.6 lb ft^{-3})]) was two-thirds of the value at the Field site (1.44 g cm^{-3} [(89.9 lb ft^{-3})]), and was significantly different throughout the soil profile except for the 20 to 30 cm (8 to 12 in) depth. These results show that row crop management and its effect on soil loss have significantly altered the hydraulic properties for this soil. Results from this study increase our understanding of the effects of long-term soil management on soil hydraulic properties.

Introduction

An essential goal of the Conservation Effects Assessment Project (CEAP) is to investigate the impact of various conservation practices and their spatial positioning on water and soil quality within a watershed (Duriancik et al. 2008). Simulation modeling is extensively used to assess the impacts of conservation practices on water quality in watersheds. The accuracy of simulation modeling depends upon using reliable and precise input data. Hydrologic simulation models are highly sensitive to soil hydraulic properties, which strongly influence model output related to water quality (Spruill et al. 2000; White and Chaubey 2007; Feyereisen et al. 2007).

Soil hydraulic properties are dynamic and are affected by many factors. These factors include soil structure (Fuentes et al. 2004), biological plants and organisms which grow and decay (Beven and Germann 1982; Meek et al. 1992), shrink-swell cracks in clay soils (Baer and Anderson 1997), and agricultural activities such as tillage and traffic compaction (Udawatta et al. 2008; Fuentes et al. 2004). Erosion is also an important process because it can degrade soil physical properties (Lal and Moldenhauer 1987; Arriaga and Lowery 2003). A major impact of erosion is often the removal of a coarser textured topsoil and exposure of a finer textured-subsoil at the surface that often has higher bulk density and lower hydraulic conductivity (Seobi et al. 2005; Jagadamma et al. 2009). Perennial vegetation is an additional factor which can reduce the amount of surface runoff and the rate of erosion (van Rompaey et al. 2001); this perennial vegetation may also create differences in soil hydraulic properties (Jiang et al.2008).

Seobi et al. (2005) found soil under perennial grass and tree buffers had lower bulk density and higher porosity than soil under row crop areas. They also concluded that six years after establishing the buffers, soil under buffers can store more water and hence would have lower runoff and less sediment, nutrient, and herbicide losses. Similarly, Rachman et al. (2004) showed that areas under perennial grass hedges for more than ten years had lower bulk density and clay content and higher porosity and saturated hydraulic conductivity than areas under row crop cultivation for the same soil. Skaggs et al. (2006) studied the effects of forest management on saturated hydraulic conductivity (K_{sat}) and found K_{sat} values for a mature plantation forest were 20 to 30 times higher than values given in the soil survey for the study area. They attributed this deviation in K_{sat} values to the difference in land management.

These variations in soil hydraulic properties are probably caused by perennial vegetation compared to annual row crop management. This perennial vegetation increases soil porosity which in turn strongly influences soil hydraulic properties (Seobi et al. 2005; Udawatta et al. 2008). Under perennial vegetation, the soil is not disturbed with tillage unlike annual row crop management; this perennial management maintains better soil bulk density and hydraulic properties over the long-term (van Dijck and van Asch 2002; Fuentes et al. 2004; Assouline, 2006).

While management can affect soil properties through soil compaction and root processes, long-term management could have additional effects because of erosion and loss of the top soil layer. Soil erosion critically reduces plant production when a topsoil silt loam layer becomes thinner and a subsoil high in clay content is exposed (Larson et al. 1983; Pierce et al. 1983; Scrivner et al. 1985). This is a typical feature of soils in Major Land Resource Area 113, Central Claypan Area, where an argillic horizon high in clay content (> 50%) is overlaid by silt loam (Blanco-Canqui et al. 2002; Lerch et al. 2005). Removal of the silt loam layer because of erosion exposes the high clay content layer; Pierce et al (1983) found that erosion of these types of soils disproportionately reduces crop productivity. Kitchen et al (2005), in a study on claypan soils, found that crop yield is highly variable and could be better represented by topography and clay depth as measured using an electrical conductivity sensor than with an Order 1 Soil Survey. Lerch et al (2005) concluded from a study in claypan soils that long-term variability in soil loss was able to explain the patterns of soil quality, water quality, and crop yield. This loss of topsoil not only reduces crop productivity but also augments the detrimental impact on soil and water quality; Mudgal et al. (2008) in a simulation study concluded that there is more probability of increased runoff and atrazine loss from areas with shallow claypan soils.

Jiang et al. (2007a) examined the impact of four conservation management systems, mulch till, no-till, CRP (Conservation Resource Program) and perennial hay, on soil hydraulic properties influenced by landscape position on claypan soils. They found that most of the effects of management were limited to the top 10 cm (4 in) of soil. Below this depth, soil hydraulic properties were more dependent on the depth from the surface to the claypan. At the backslope position, which had the shallowest depth to claypan, they found the lowest K_{sat} in comparison to summit and footslope positions. They concluded from the four management practices that the use of perennial grasses improved soil hydraulic properties the most.

The objective of this study was to quantify the impact of two long-term management systems on soil water retention, pore size distributions, bulk density, and saturated hydraulic conductivity. It has been hypothesized that for similar soils, differences in long-term management practices can have a significant impact on soil hydraulic properties. To evaluate this hypothesis, soil hydraulic properties were compared for a field under row crop cultivation for over 100 years and for a native prairie that has never been tilled. Comparison of soil hydraulic properties because of long-term soil erosion could help in understanding the impact of topsoil loss especially in claypan areas.

Materials and Methods

Experimental Site

Two sites were selected (figure 3.1): one under long-term row crop management that has been under cultivation for more than 100 years (Field) and one under native prairie (Tucker Prairie, TP) which has never been tilled (table 3.1). The Field site is located near the town of Centralia in central Missouri. Presently this site is managed by the USDA-ARS Cropping Systems and Water Quality Unit (Lerch et al. 2005).

The historical management records for the Field site were presented by Lerch et al. (2005). They found that during the earlier half of the 20^{th} century, the most likely crops were corn and wheat under plow and disk tillage. During the later part of the century, plowing and disk tillage were continued but the cropping system could be described with more confidence as corn, soybean and grain sorghum. After 1991, the field was under uniform management with a corn/soybean rotation with mulch tillage.

Tucker Prairie (TP) is an un-tilled native prairie (Dahlman and Kucera, 1965) that is also located in central Missouri and is under native vegetation. The major species found in the prairie include big blue stem (*Andropogon genardi* Vitman.), little blue stem (*Schizachyrium scoparium* Nash.), prairie dropseed (*Sporobolus heterolepis* [A. Gray] A. Gray), and Indian grass (*Sorghastrum nutans* [L. J. Nash]) (Udawatta et al. 2008). Kucera et al. (1967) stated that other than fire the only source of soil disturbances in the prairie were microbial processes, small rodents and insects.

Soils at both the sites are classified as Mexico silt loam (fine, smectitic, mesic Vertic Epiaqualfs). Mexico soils are mostly located on ridges or hillsides having slopes of 0 to 4% and are formed in loess over loamy sediments derived from glacial till. These soils are poorly drained mainly because of the presence of an argillic claypan horizon that is 10 to 30 cm (3.9 to 12 in) deep below the surface (Ghidey and Alberts 1999). Table 3.1 shows that the Bt horizon at the Field site starts at approximately the 30 cm (12 in) soil depth whereas at the TP site this horizon starts after 40 cm (16 in) of soil, with the clay content in the Field site being slightly higher for its Bt horizon than for the TP site.

Soil Sampling and Analysis

Sampling was done during the summer of 2008 at both sites. Intact soil cores of 7.6 cm (3 in) diam. and 7.6 cm (3 in) length were taken to determine soil water retention, bulk density and K_{sat}. At each site, six replicate points were selected and from each replicate point six cores were collected from 0 to 60 cm (0 to 24 in) depth in the center of

10 cm (4 in) increments. Once the samples were collected in aluminum rings, they were enclosed with two plastic covers on the top and bottom, labeled, and transported to the laboratory. Soil samples were stored in a refrigerator at 4°C (39°F) until analyses were conducted.

Soil cores were taken from the refrigerator, covered with cheese cloth on the bottom, and then saturated in a plastic tray. Once the samples were saturated, the gaps between the soil core and aluminum ring were sealed using a bentonite solution. The constant head method was used to measure K_{sat} (Klute and Dirksen 1986), except if the flow rate of water through the soil core was less than 1 mm per hour, K_{sat} was measured using the falling head method as described in Klute and Dirksen (1986). The electrical conductivity of the water was 0.68 dS m^{-1} and the sodium absorption ratio was 2.34.

After K_{sat} measurements, soil water retention was determined at 0.0, -0.4, -1, -2.5, -5, -10, and -20 kPa (0.0, -0.06, -0.15, -0.36, -0.73, -1.45, and -2.9 lb in^{-2}) soil water pressures using Buchner funnels; the pressure plate method was used for lower soil water pressures at -33, -100, and -1500 kPa (Klute and Dirksen 1986 [(-4.8, -14.5, and -217.6 lb in^{-2})]). Soil cores were then air dried and weighed. A sub-sample from each core was oven dried at 105°C (221°F) for 24 h. Bulk density was determined from air dried samples corrected to an oven dry weight.

Soil water retention data were used to estimate the van Genuchten parameters. The van Genuchten (1980) function describes the soil water retention curve (Lu et al. 2007) as

$$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha h)^n\right]^{\left(\frac{1}{n}-1\right)} \quad (1)$$

where θ is the volumetric water content, θ_r and θ_s are the residual and saturated water contents respectively, and h is the hydraulic head. The parameters α, n, and m ($m = 1 - 1/n$) are fitting parameters. During the curve fittings, θ_r was always taken as zero and θ_s values were used as measured in the laboratory. For all the soil samples, α and n values were fitted using Equation 1 with the RETC computer program (van Genuchten et al. 1991).

Soil water pressure data was used to estimate the effective pore size using the capillary rise equation (Jury et al. 1991). Pore sizes were divided into four different classes: macropores (>1000 μm [(>0.039 in)] effective diam.), coarse mesopores (60 to 1000 μm [(0.0024 to 0.039 in)] effective diam.), fine mesopores (10 to 60 μm [(0.00039 to 0.0024 in)] effective diam.), and micropores (<10 μm [(<0.00039 in)] effective diam) as were used in Rachman et al. (2004).

The year 2008 was an unusually wet year, which produced a perched water table at both sites during the summer. In June, a shallow water table technique (auger hole method) was used to measure saturated hydraulic conductivity K_{sat}. At both sites, nine to twelve replicate points were assessed (Klute and Dirksen 1986).

Statistical Analysis

Analysis of variance (ANOVA) was performed using the GLM procedure (SAS Institute, 1999) at the 95 % significance level to test differences between treatments (Field and TP), depths, and treatment by depth interactions. Significant differences between treatment or depth means were assessed by using least significant differences at the 95% probability level (Duncan's LSD). For fitting the van Genuchten parameters, the coefficient of determination was used for assessing the fit with values above 0.85.

Results

Soil Water Retention

Treatment factors were different at all soil water pressures except two, -20.0 and -33.0 kPa ([(-2.9 to -4.8 lb in^{-2})]; table 3.2). Soil water retention values as a function of soil depth for all measured soil water pressures were found to be different (table 3.2). Generally, soil water retention at pressures higher than -33 kPa (-4.8 lb in^{-2}) was greater for the first and sixth depth, and was lower for the second and/or third depth; this can be attributed to variations in clay content throughout the profile (table 3.1). Interactions between treatment and depth were significant for all the soil water potentials. This was attributed to the differential clay content profile between the two sites.

Differences between the treatments for specific soil depths are shown in figure 3.2. For the TP treatment, soil water content was much higher than the Field treatment for the first depth at soil water pressures < -20 kPa (-2.9 lb in^{-2}). For the fourth depth (30 to 40 cm [(12 to 16 in)]), water content is higher at the Field site than at the TP site for all pressures. This is attributed to the claypan being at a shallower depth for the Field site because erosion has occurred to a greater extent with continuous cultivation.

At the fifth depth (40 to 50 cm [(16 to 20 in)]), water contents for higher pressures were not different between the treatments. This result was attributed to these two treatments having similar clay content at the fifth depth (table 3.1). At the sixth depth (50 to 60 cm [(20 to 24 in)]), the soil water content trend showed the TP site had significantly higher water content than the Field site at all pressures. This was because of the clay content decreasing at this depth for the Field site while the clay content remained high for the Tucker site. The claypan depth change is a result of the erosion which has taken place at the Field site compared to less erosion at the TP site.

van Genuchten Parameters

The soil water characteristics for the sites and depths of this study were well described by the van Genuchten relationship (r^2 values > 0.85). The fitted van Genuchten parameters for the treatments and soil depths are listed in table 3.3. The n values for both treatments were less than 2. The α values, which are the inverse of the air-entry potential (Fuentes et al. 2004), were always less than 0.2. The effects of soil depth on these parameters are illustrated in figure 3.3. The α parameter was significantly higher for the TP site at the surface depth and significantly lower for the fifth depth than at the Field site.

Pore Size Distributions

Long-term soil management treatments (TP and Field sites) had significant effects on coarse and fine mesopores (table 3.4). No significant effects were found for treatments on macropores.

Coarse and fine mesoporosity for the Field site were 0.044 and 0.053 $m^3\ m^{-3}$ ([(0.044 and 0.053 $in^3\ in^{-3}$)]; table 3.4), respectively, values almost half those for the TP site of 0.081 and 0.086 $m^3\ m^{-3}$ (0.081 and 0.086 $in^3\ in^{-3}$), respectively.

Pore size classes significantly changed with soil depth (table 3.4). Least significant differences between treatments for a specific depth or different depths are shown in figure 3.4. Coarse and fine mesopores both were significantly higher for the TP site than for the Field site for the upper four and three soil depths, respectively; for deeper depths, the impact of soil structure decreased between the treatments. Significant differences in micropores were found at only the fourth and sixth depths. The higher amount of micropores in the fourth depth and the lower amount of micropores in the sixth depth for the Field site than for the TP site is because of the shallower clay depth found at the Field site in comparison to the TP site (table 3.1). After 50 cm (20 in) of soil, the clay content at the Field site starts to decrease while it is still increasing at the TP site. It further supports the argument of greater topsoil loss from the Field site, which has been under cultivation for over 100 years, than from the native prairie, which has never been tilled (Lerch et al. 2005).

Bulk Density

Bulk density was found to be different between the treatments, soil depths, and also for the interaction between treatment and soil depth (table 3.4). Bulk density was higher for the Field site than for the TP site.

Bulk density was significantly different for all the depths between both treatments except for the third depth (20 to 30 cm [(7.9 to 12 in)]; figure 3.5). Because of the higher root density at the TP site, the bulk density at the soil surface was less than 1 g cm^{-3} (62.4 lb ft^{-3}). After the first depth, the effect of roots begins to diminish and the bulk density increases for the TP site. After the fourth depth, there was increase in clay content which resulted in a lower bulk density. At the Field site, the bulk density was lowest for the fourth depth (30 to 40 cm [(12 to 16 in)]) where the clay percentage was the highest; after this depth, bulk density increased with a reduction in clay content.

Saturated Hydraulic Conductivity

There were differences in K_{sat} between treatments, soil depths, and for treatment and depth interactions (table 3.4). The K_{sat} was higher for the TP site than the Field site averaged across soil depths (table 3.4). K_{sat} for the TP site was almost 20 times higher than the Field site even though the samples were collected from the same soil series. Thus because of the changes in long-term management, there were considerable differences in K_{sat}. These differences were more extreme than found in the literature on similar soils. Seobi et al. (2005) found that K_{sat} was 14 times higher for agroforestry buffers than for row crop management. In another study by Fuentes et al. (2004), researchers found that K_{sat} values of soils under native prairie were almost 10 times higher than of soils under conventional tillage and no-till management.

The measured K_{sat} values for the TP site were always higher than the Field site (figure 3.6), although significant differences occurred only in the first depth because of the high variability of this property. K_{sat} for the surface soil at the TP site was almost 57 times higher than the Field site. After the third depth, K_{sat} at the Field site drops by an order of magnitude, from 5 to 0.3 mm h^{-1} (0.197 to 0.012 in h^{-1}). This might be because of the abrupt change in clay percentage in the soil at the Field site. A similar drop of K_{sat} for the TP site was found to occur after the fourth depth, from 17 to 1 mm h^{-1} (0.67 to 0.039 in h^{-1}). Therefore at the Field site, the downward movement of water reduces to a very low rate after 30 cm (12 in), and at the TP site, this clay barrier for restricted downward movement of water occurs after 50 cm (20 in). At the TP site, there is a thicker silt loam soil profile that can absorb more water than at the Field site; hence there will be a greater probability of more surface runoff occurring from the Field site (Mudgal et al. 2008).

Discussion

Soil Water Retention

The Mexico soil has an argillic horizon underneath the silt loam surface horizon and the depth of the argillic horizon dominates many major hydrologic processes (Mudgal et al. 2008). These processes are dependent on soil hydraulic properties. Variations in soil hydraulic properties were associated with variation in clay content and depth to argillic horizon. The mean soil water contents for all soil water pressures greater than -33 kPa (-4.8 lb in^{-2}) at the TP site averaged across all soil depths were always higher than values for the Field site , but were lower for other pressures (table 3.2). This might be attributed to the higher clay content for more depths at the Field site (table 3.1). A similar trend was found by Scott and Wood (1989) in a study in silt loam (Albaqualf) soils; they found that for surface soil under cultivation for 30 years and a virgin prairie, soil water retention at -30 and -1500 kPa (-4.4 to -217.6 lb in^{-2}) were not significantly different, whereas water retention was significantly different for other pressures (higher water pressures).

Differences in soil water retention for the first three depths could be attributed to management variations but for deeper depths differences were more dependent on clay content. We presume the differences in soil water retention for upper layers were because of the higher root density of the perennial grasses and forbs which improved soil structure in the soil surface layers for the native prairie site (TP) compared to annual cultivation for the Field site. Fuentes et al (2004) found similar results with soils under native prairie having better soil structure than fields under cultivation. Soil water content for the TP site was significantly higher at all pressures above -33 kPa (-4.8 lb in^{-2}) for the top two soil depths; this was attributed to better root development in the TP site and better soil structure near the surface.

Another noticeable feature with the water retention data is that the curves for pressures > -20 kPa (-2.9 lb in^{-2}) appear to be relatively unchanged with soil depth for the Field site (figure 3.2). This is likely due to several factors. In the upper two soil depths, traffic compaction over time has reduced the porosity compared to the native prairie site. In addition, reductions in organic matter (table 3.1) at shallow depths because of annual tillage and cultivation have occurred at the Field site for the past 100 years. For the third depth, the effects of cultivation management on water retention are less pronounced (figure 3.2). For the fourth depth, water retention at the Field site is higher because ofdifferences in clay content in the profile compared to the prairie site (differential erosion). For the fifth depth, water retention values are similar because of similar levels of clay content (prairie increasing in clay and field site decreasing in clay). By the sixth depth, the clay content has decreased for the Field site and is now at a maximum for the TP site; the effects on water retention can be observed in figure 3.2.

van Genuchten Parameters

The n values found in present study were in accordance with the values found by Ippisch et al. (2005); they also found n value ranging from 1 to 2 for fine textured soils. Statistical comparisons for α and n values between the treatments and soil depths are shown in figure 3.3. No general trend was found, but the α parameter was significantly higher for the TP site at the surface depth and significantly lower for the fifth depth than at the Field site. These differences are attributed in part to those discussed earlier in the water retention section.

Pore Size Distributions

Results from the current study were similar to those found by Seobi et al. (2005) in a study near Novelty, Missouri. They did not find any significant differences in macroporosity between soils under row crop management and agroforestry buffers for a Putnam silt loam (claypan soil) using similar measurement techniques to those in the present study. Other researchers using a different method have found differences (Udawatta et al. 2008). Using x-ray computed tomography, Udawatta et al. (2008) in similar soils (Epiaqualfs) found significantly higher levels of macroporosity (>1000 μm [(>0.039 in)] effective diam.) for native prairie and CRP (Conservation Reserve Program) than for soils under row crop cultivation. Computed tomography methods may be better suited to detecting differences in macroporosity than estimates from water retention curves (Gantzer and Anderson, 2002). However, the computed tomography method does not provide good estimates for the full range of mesopores.

Similarly, the management effect was visible for pore size distribution results in coarse and fine mesopores for the upper three soil depths; this can be attributed to the influence of past compaction for the Field site and better structure for the TP site. As found in the TP site, major vegetation included native grasses and forbs that have a more shallow depth distribution of roots than does tree vegetation (Udawatta and Henderson, 2003; Seobi et al. 2005). The variations in micropores were more dominated by differential clay content and therefore they were significantly different at depths where clay content at the two sites was different, as was explained in the results section.

Bulk Density

The impact of long-term management was clearly visible on bulk density results. These differences can be attributed not only to vehicular traffic at the Field site, but also to tillage. Rousseva et al. (1988) and Or et al. (2000) found that after tillage operations, cycles of wetting and drying might cause an increase in soil bulk density due to reconsolidation. The differences in bulk density because of soil depth were mainly due to differences in structure and texture. The lowest bulk density was found in the first depth for the TP site, which could possibly be attributed to higher root density. The maximum bulk density was found for the Field site in the second depth. The lowest value for the Field site was found in the fourth depth and for the TP site the second lowest value was found in the sixth depth . These low values were found where the maximum expression of smectitic clays was encountered. Similar trends for bulk density were found by Jiang et al. (2007a). For the 0 to 10 cm depth (0 to 3.9 in), the CRP treatment had the lowest bulk density (1.07 g cm^{-3} [67 lb ft^{-3}]) and the mulch till had the highest (1.25 g cm^{-3} [78 lb ft^{-3}]) (Jiang et al. 2007a). They concluded that the management effect was limited only to this upper depth with deeper effects dominated by the clay content of the specific horizons.

Saturated Hydraulic Conductivity

The differences in K_{sat} values for the top depths were more dependent on soil structure variations which were affected by land management. K_{sat} differences for lower depths were because of distinction in clay content. Jiang et al (2007a) in similar soils (Epiaqualfs) compared soil hydraulic properties among four different management systems and three landscape positions. They inferred that the differential claypan depth is a controlling factor on soil hydraulic properties. They found K_{sat} differences were strongly affected by management at the backslope position, where the claypan was shallowest compared to other landscape positions. At the summit and footslope landscape positions, they did not find significant differences because of management. The present study did not evaluate the effects of landscape position but found substantially different K_{sat} values as affected by long-term management.

The K_{sat} values measured by the auger hole method were not significantly different compared to values of K_{sat} measured by the core sampling method (table 3.5). The average value for the Field site was 5.02 mm h^{-1} (0.198 in h^{-1}) while the value for the TP site was 62.9 mm h^{-1}(2.48 in h^{-1}). The auger hole method measures a horizontal saturated hydraulic conductivity while the core sampling method measures a vertical conductivity. Therefore, it can be concluded that K_{sat} was isotropic for these two sites.

The SSURGO (Soil Survey Geographic Database; Soil Survey Staff, 2008) database is one of the most common databases for acquiring soil properties in the United States of America. This database provides the values of soil parameters in ranges. The value of K_{sat} for Mexico silt loam in the database is 14.4 to 50.4 mm h^{-1} (0.57 to 1.98 in h^{-1}) for the surface layer. In the present study, K_{sat} at Field site was 5.55 mm h^{-1} (0.22 in h^{-1}), which is 62% lower than the lowest value given in SSURGO for the surface soil. The K_{sat} for TP site surface layer was 316 mm h^{-1} (12.4 in h^{-1}), almost 6 times higher than the highest K_{sat} value given in SSURGO. This shows that the long-term management has changed K_{sat} properties to a larger extent than what could be expected from the range of values given in SSURGO. K_{sat} values are especially sensitive parameters of hydrologic simulation models when permeability is low or when there is a restrictive layer (Mudgal et al. 2008), and variation to this degree could significantly affect the output of studies predicting future impacts of different conservation practices on soil and water quality.

Conclusions

A study was conducted to quantify and compare the effects of long-term soil and crop management on soil hydraulic properties: soil water retention, pore size distribution, bulk density, and saturated hydraulic conductivity. Two different management systems were selected: a native prairie that has never been tilled (Tucker Prairie; TP) and a field that has been under row crop cultivation for more than 100 years (Field). Measured soil water retention curves showed that the Field site had lower soil water content for all pressures above -33 kPa (-4.8 lb in^{-2}), but for pressures at and below -33 kPa (-4.8 lb in^{-2}), water content was higher at the TP site for the top two soil layers (0 to 10 cm and 10 to 20 cm [(0 to 3.9 in and 3.9 to 7.9 in)]). Coarse (60 to 1000 μm [(0.0024 to 0.039 in)] effective diam.) and fine mesoporosity (10 to 60 μm [(0.00039 to 0.0024 in)] effective diam.) values were lower for the Field site (0.044 and 0.053 m^3 m^{-3} [(0.044 and 0.053 in^3 in^{-3})]) and were just over half those for the TP site (0.081 and 0.086 m^3 m^{-3} [(0.081 and 0.086 in^3 in^{-3})]). Bulk density at the TP site for the surface soil (0 to 10 cm [(0 to 3.9 in)]) was 0.81 g cm^{-3} (50.6 lb ft^{-3}), which was two-thirds of the value at the Field site (1.44 g cm^{-3} [(89.9 lb ft^{-3})]). Bulk density at the TP site was significantly different than at the Field site for all except for the third depth (20 to 30 cm [(7.9 to 12 in)]). Saturated hydraulic conductivity (K_{sat}) was almost 57 times higher at the TP site (316 mm h^{-1} [(12.4 in h^{-1})]) than at the Field site (5.55 mm h^{-1} [(0.219 in h^{-1})]). This difference was likely caused by the differences in porosity and bulk density.

Variations in soil hydraulic properties could be explained by the differences in land cover and management (compaction, tillage) but also by the loss of topsoil and the thinning of the layer above the claypan. Extensive agricultural practices over the last 100 years at the Field site have reduced the topsoil by almost 20 to 30 cm in comparison to the TP site that had never been tilled. The problem is likely to get worse as time progresses since higher bulk density, lower soil water capacity, and lower hydraulic conductivity increase the runoff potential and soil erosion. Therefore, it is expected that surface runoff and associated pollutant loads will be higher for the Field treatment than for the TP treatment.

Thus, loss of productivity and increased environmental impacts are likely to be more pronounced in those areas that are eroded. As found by Jiang et al. (2007a), fields could be delineated by landscape position and conservation management targeted to more vulnerable landscapes. In addition, apparent electrical conductivity can be used to quantify variations in depth to claypan throughout fields and these data used to predict variations in hydraulic properties (Jiang et al, 2007b).

Selection of various soil and water conservation practices and their efficiency depends upon soil hydraulic properties. This study concludes that soil hydraulic properties are significantly different for the same soil series when fields are under substantially different management. Therefore, soil hydraulic parameters used for predictive purposes should be adjusted based on soil management in addition to soil mapping units.

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Tables

Table 3. 1: Physical and chemical properties of typical soil profiles for Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites.

Soil Horizon	Soil Depth	Clay	Silt	CEC	Organic carbon	pH (water)
	cm	------ % (g/g) -------		$cmol_c\ kg^{-1}$	$g\ kg^{-1}$	
			Field			
Ap	0-24	14.0	81.9	13.6	8	4.9
E	24-34	20.4	72.0	16.4	6	4.7
Bt1	34-45	54.0	43.4	37.8	9	4.7
Bt2	45-65	56.6	41.8	39.9	8	4.6
			TP*			
A	0-20	18.9	74.3	19.3	36	5.2
AE	20-25	20.4	72.5	14.3	13	5.0
E	25-36	21.5	70.7	14.8	9	4.9
EB	36-41	24.9	68.1	16.3	8	5.0
Bt1	41-56	50.6	46.7	33.0	11	4.8

* Source: Udawatta et al. 2008.

Table 3. 2: Soil water content means for treatments and depths along with analysis of variance (ANOVA) probability values over a range of soil water pressures; Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites.

Mean	***Soil water pressure, kPa***									
	0.0	**-0.4**	**-1.0**	**-2.5**	**-5.0**	**-10.0**	**-20.0**	**-33.0**	**-100.0**	**-1500.0**
	Volumetric water content, $m^3\ m^{-3}$									
Treatment										
Field	0.509	0.479	0.464	0.448	0.435	0.423	0.409	0.383	0.303	0.185
TP	0.570	0.541	0.516	0.487	0.460	0.440	0.419	0.374	0.278	0.147
Depth, cm										
0 – 10	0.594	0.553	0.518	0.477	0.447	0.427	0.403	0.345	0.243	0.103
10 – 20	0.508	0.486	0.471	0.448	0.420	0.395	0.370	0.348	0.209	0.100
20 – 30	0.501	0.489	0.473	0.443	0.413	0.389	0.368	0.348	0.248	0.130
30 – 40	0.528	0.495	0.473	0.448	0.428	0.411	0.396	0.374	0.306	0.170
40 – 50	0.533	0.493	0.473	0.463	0.460	0.453	0.443	0.396	0.338	0.233
50 – 60	0.573	0.543	0.534	0.525	0.517	0.514	0.505	0.461	0.401	0.259
	ANOVA, *P* > *F*									
Treatment	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0008	0.0257	0.2223	0.2015	0.0179	0.0102
Depth	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Treatment by Depth	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Table 3. 3: Fitted van Genuchten parameters as a function of depth for the Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites.

Soil Depth **cm**	***Fitted parameters****					
	Field			**TP**		
	θ_s $cm^3\ cm^{-3}$	**n** -	**α** cm^{-1}	**θ_s** $cm^3\ cm^{-3}$	**n** -	**α** cm^{-1}
0 – 10	0.484 (0.460, 0.526)^	1.255 (1.210, 1.322)	0.021 (0.008, 0.042)	0.706 (0.677, 0.723)	1.207 (1.180, 1.230)	0.100 (0.051, 0.153)
10 – 20	0.463 (0.440, 0.496)	1.242 (1.182, 1.289)	0.020 (0.012, 0.052)	0.554 (0.491, 0.631)	1.339 (1.241, 1.568)	0.025 (0.004, 0.070)
20 – 30	0.491 (0.454, 0.543)	1.165 (1.108, 1.220)	0.044 (0.016, 0.134)	0.512 (0.488, 0.543)	1.274 (1.227, 1.303)	0.021 (0.011, 0.035)
30 – 40	0.553 (0.480, 0.634)	1.123 (1.103, 1.164)	0.072 (0.010, 0.174)	0.505 (0.483, 0.541)	1.181 (1.137, 1.243)	0.074 (0.034, 0.139)
40 – 50	0.520 (0.489, 0.544)	1.069 (1.050, 1.084)	0.146 (0.078, 0.210)	0.545 (0.496, 0.595)	1.171 (1.135, 1.212)	0.047 (0.013, 0.117)
50 – 60	0.544 (0.516, 0.623)	1.153 (1.135, 1.181)	0.015 (0.011, 0.024)	0.604 (0.590, 0.624)	1.135 (1.103, 1.162)	0.012 (0.006, 0.021)

* θ_r residual water content value was set to zero.
^ Values in parentheses are minimum and maximum values.

Table 3. 4: Treatment and depth means along with analysis of variance (ANOVA) probability values for saturated hydraulic conductivity (K_{sat}), bulk density (BD), macroporosity, coarse mesoporosity, fine mesoporosity, and microporosity for the Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites.

Mean	*Macroporosity (>1000 µm)*	*Coarse mesoporosity (60 to 1000 µm)*	*Fine mesoporosity (10 to 60 µm)*	*Microporosity (<10 µm)*	*Ksat*	*BD*
Treatment			**--------------------------- cm^3 cm^{-3} ---------------------------**		**mm h^{-1}**	**g cm^{-3}**
Field	0.030	0.044	0.053	0.383	4.313	1.350
TP	0.030	0.081	0.086	0.374	87.66	1.131
Depth, cm						
0 – 10	0.042	0.106	0.103	0.345	175.9	1.128
10 – 20	0.023	0.066	0.073	0.348	62.79	1.304
20 – 30	0.013	0.076	0.066	0.348	21.49	1.292
30 – 40	0.033	0.065	0.054	0.374	12.58	1.242
40 – 50	0.039	0.036	0.064	0.396	3.160	1.273
50 – 60	0.030	0.027	0.055	0.461	0.020	1.206
			ANOVA, *P* > *F*			
Treatment	0.8541	< 0.0001	< 0.0001	0.2015	0.0004	< 0.0001
Depth	0.0119	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Treatment by Depth	0.5443	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Table 3. 5: Comparison of saturated hydraulic conductivity (K_{sat}) values measured by auger hole and core sampling methods for the Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites.

Replicate points[$]	Depth[*]	K_{sat}	
		Auger Hole[^]	Core Sampling[#]
	cm	mm h^{-1}	mm h^{-1}
		Field	
1	0 – 35	3.43	1.21
2	1 – 35	4.74	5.84
3	2 – 42	6.79	9.38
4	2 – 40	5.10	2.14
		TP	
1	5 – 40	72.5	65.4
2	5 – 43	32.1	18.4
3	12 – 42	92.9	41.2
4	12 – 45	71.0	43.2
5	6 – 50	46.9	7.75
6	18 – 43	73.7	35.0

$ Six replicate points chosen for sampling in Mexico silt loam soil.
* Depth from water table to the bottom of hole used to measure K_{sat} by auger hole method.
^ Geometric mean K_{sat} of two holes per replicate point.
# Effective K_{sat} for soil depths corresponding to auger hole method.

Figures

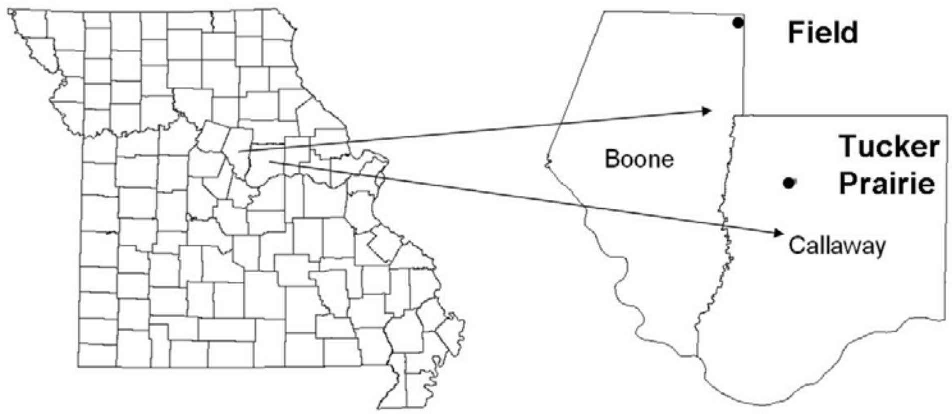

Figure 3. 1: Location of study sites, Field (39° 13’ 48”N, 92° 7’ 12” W), and Tucker Prairie (38° 57’ 4” N, 91° 59’ 30” W).

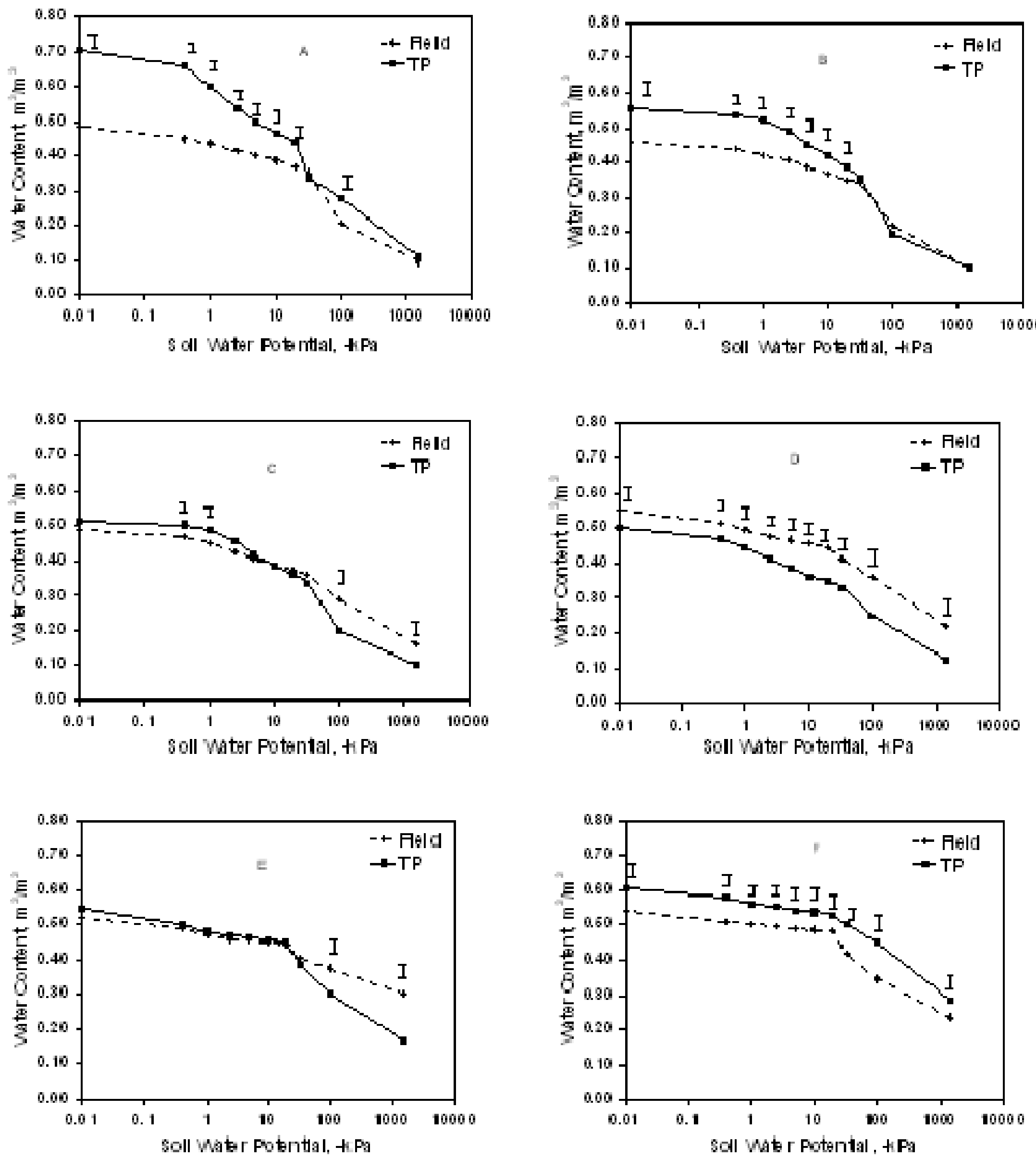

Figure 3. 2: Effects of management on soil water retention for the following depths: (A) 0 to10 cm, (B) 10 to 20 cm, (C) 20 to 30 cm, (D) 30 to 40 cm, (E) 40 to 50 cm, and (F) 50 to 60 cm. Values are for Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites. Bars indicate LSD (0.05) values for a specific soil water pressure when significant differences occurred; these values are same for all depths.

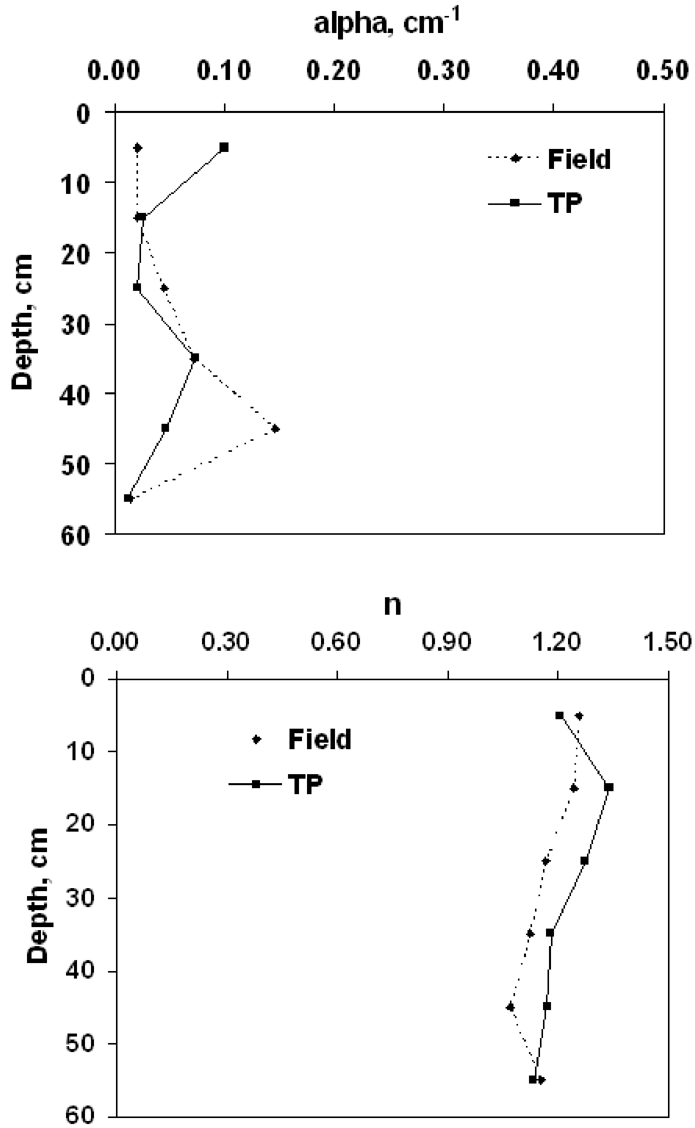

Figure 3. 3: Effects of management and depth on fitted van Genuchten parameters *α* and *n*. Values are for Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites. Bars indicates LSD (0.05) values.

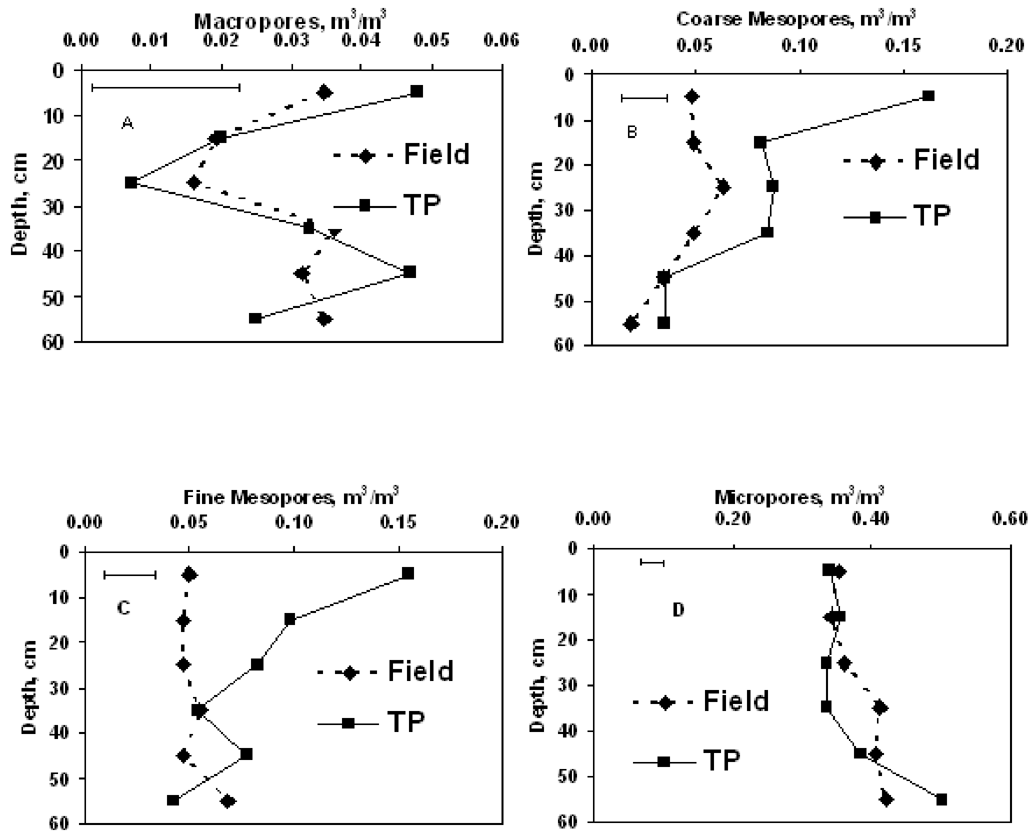

Figure 3. 4: Effects of management and depth on porosity for selected pore size classes: (A) macropores (>1000 µm diam.), (B) coarse mesopores (60 to 1000 µm diam.), (C) fine mesopores, (10 to 60 µm diam.), and (D) micropores (< 10 µm diam.). Values are for Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites. Bars indicates LSD (0.05) values.

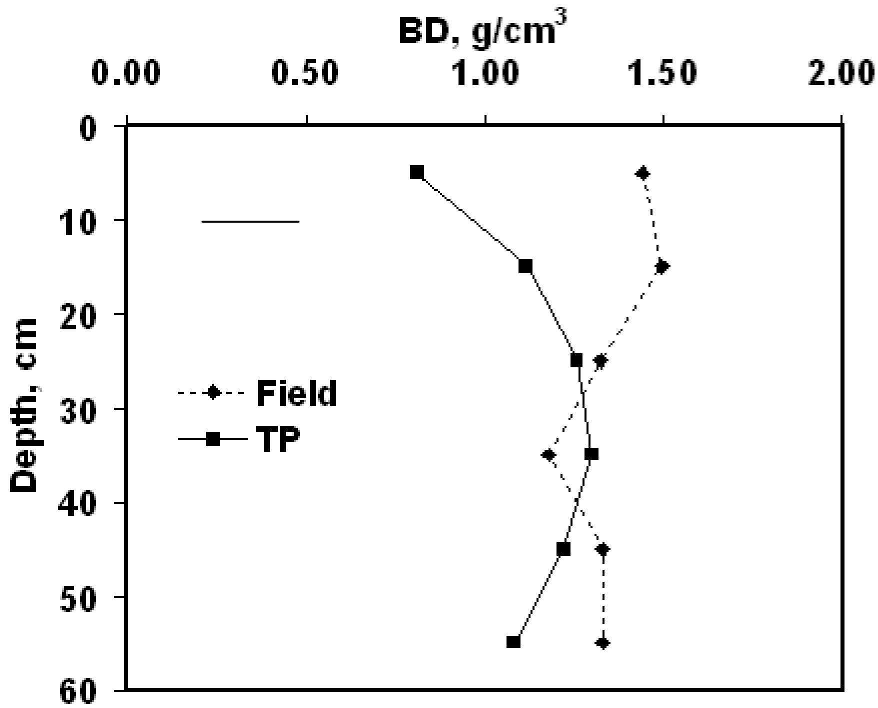

Figure 3. 5: Effects of management and depth on bulk density (BD). Values are for Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites. The bar indicates the LSD (0.05) value.

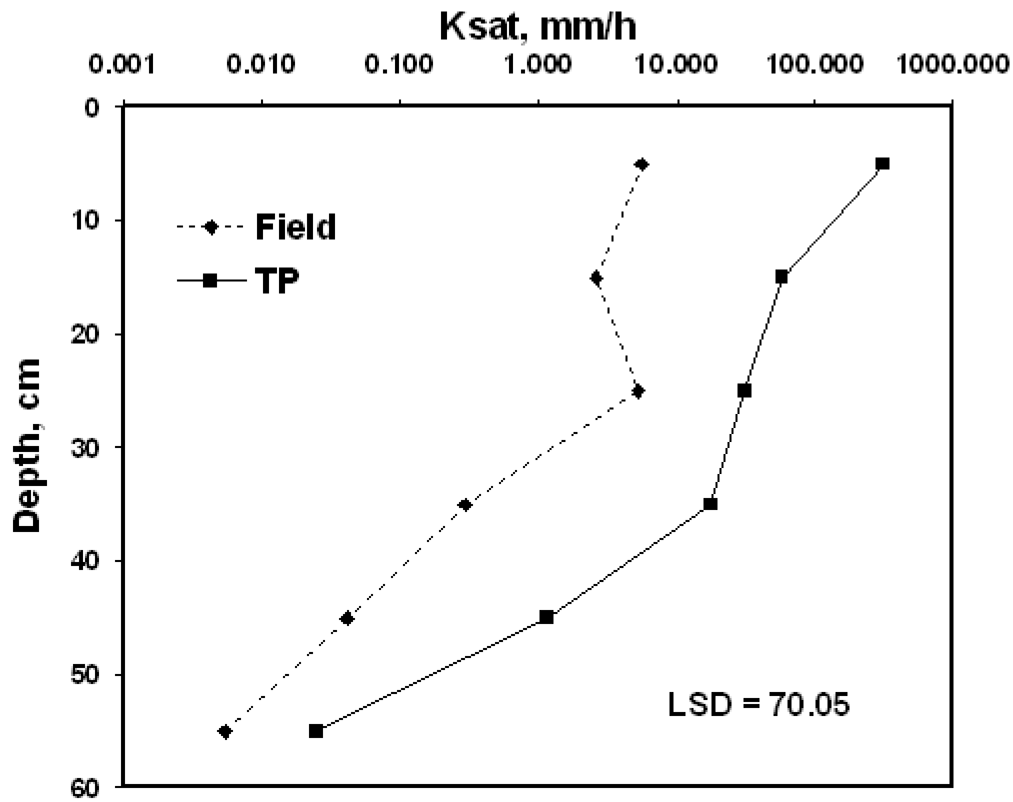

Figure 3. 6: Effects of management and depth on saturated hydraulic conductivity (Ksat). Values are for Field (field under long-term row crop management) and TP (Tucker Prairie, never been tilled) sites. The LSD (0.05) value is listed on the graph because of log scale.

CHAPTER 4

APEX MODEL ASSESSMENT OF VARIABLE LANDSCAPES ON RUNOFF AND DISSOLVED HERBICIDES

Abstract

Variability in soil landscapes and their associated properties can have significant effects on erosion and deposition processes that affect runoff and transport of pesticides. Simulation models are one way in which the effects of landscapes on these processes can be assessed. This simulation study evaluated the effects of variations in landscape position on runoff and dissolved atrazine utilizing a calibrated farm- and field-scale Agricultural Policy/Environmental eXtender (APEX) model. Twelve agricultural plots (18 x 189 m^2) in the Goodwater Creek watershed, a 7250 ha agricultural area in north-central Missouri, were simulated. Plots were treated with three tillage and herbicide management systems for two grain crop rotations. Each plot contained three landscape positions: summit, backslope, and footslope along with two transition zones. Runoff was measured and samples were collected from 1997 to 2002 during the corn year of the crop rotations. Runoff samples were analyzed for dissolved atrazine. The model was calibrated and validated for each plot with event data from 1997 to 1999 and 2000 to 2002, respectively. APEX reasonably simulated runoff and dissolved atrazine concentrations with coefficients of determination (r^2) values ranging from 0.52 to 0.98 and 0.52 to 0.97, and Nash-Sutcliffe efficiency (NSE) values ranging from 0.46 to 0.94 and 0.45 to 0.86 for calibration and validation, respectively. The calibrated model was then used to simulate variable sequencing of landscape positions and associated soil properties as well

as variable lengths of landscape positions. Simulated results indicated that the runoff and the atrazine load at the plot outlet increased when the backslope length increased while keeping the steepness constant. The maximum simulated runoff among different sequences of landscape positions occurred when the backslope position was located adjacent to the outlet. Results from this study will be helpful to managers in placement of conservation practices on sensitive landscapes for improvement in water quality.

Introduction

Soil and water management are an indispensable part of agriculture. However, the use of agrichemicals such as fertilizers and herbicides in modern agricultural production systems often increases non-point source pollution. Runoff and subsequently soil erosion are two hydrologic processes responsible for water and soil quality deterioration and are impacted by local soil conditions. Claypan soils characterized by low subsoil permeability naturally possess a significant runoff potential and are especially vulnerable to elevated runoff losses of surface-applied herbicides (Ghidey et al., 2005).

Interactions between agrichemicals and soils are variable because of many factors such as environment, soil type, chemical species, and method of application. Determining the interactions of agrichemicals within soils is an important step in efficiently managing fertilizer and herbicide applications. Several researchers have found that the behaviors of herbicides and nutrients are related to soil properties such as organic carbon content (OC), cation exchange capacity (CEC) and soil pH, (e.g., Ghidey and Alberts 1999 or Drori et al. 2005). Sudduth et al. (1995) reported that in fields and plots located in claypan soil areas, there was significant spatial variability in soil nutrient concentrations, soil water holding capacity, soil pH, top soil depth, crop growth, and yield. Therefore, more site-specific approaches are necessary to reduce runoff and non-point source pollutants (Veihe, 2000; Brunner et al., 2004).

Accordingly, the primary emphasis for conservation of water quality should be to define the critical areas within fields that are generating more runoff and non-point source pollutants. Milne (1936) was among the initial researchers to propose the idea that soils are uniquely related to landscape position and to introduce the concept of a catena. He suggested the processes at one point on the landscape not only affect soil properties and processes at that position but also soil properties at down-slope landscape positions. Ruhe (1960) proposed five landscape elements: summit, shoulder, backslope, footslope, and toeslope. These elements are widely used with minor modifications (Hall and Olson, 1991) for soil studies, agricultural management, and the mitigation of non-point source pollutants. Since different landscape positions have different surface and subsurface geometries and soil properties, these positions affect various hydrologic and chemical processes occurring concurrently in the field. One approach for identifying critical areas in an agricultural field is to study the behavior of various landscape elements integrated together.

Some field experimental studies have been conducted to evaluate the contribution of different landscape positions to surface runoff, sediment load, and runoff of various nutrients and herbicides. Gabbard et al. (1998) studied the influence of topographic properties and hydrologic processes on runoff and soil erosion occurring at specific landscape positions by simulating the runoff and soil loss in the laboratory. They found there was an increased probability of more soil loss as they moved from summit to lower backslope. Naef et al. (2002) experimentally evaluated various landscape positions according to the type and characteristics of the dominant runoff processes. They then proposed cropping systems and management practices specifically adapted to each area. In order to extend these results to other landscapes, there is a need to verify that simulation models produce results that are sensitive to landscape position and to their sequence along a hillslope profile. Attention needs to be given to the processes and the amounts of runoff and pollutant loadings simulated in each landscape position.

Often, a sequence of landscape positions occurs in the order of summit, backslope and footslope, which have correspondingly different soil properties and surface topography. Jiang et al. (2007) showed that topsoil hydraulic conductivity, bulk density, and depth to claypan were significantly affected by the landscape position. In particular, bulk density was significantly higher in the footslope area at the 10-20 cm depth, followed by that of the backslope and then summit positions. At the same time, hydraulic conductivity for a tilled cropping system was one order of magnitude lower at the backslope than at the summit or footslope. But natural or man-made processes can occur that disrupt the natural sequence of these landscape positions. For example, stream bank erosion can lead to a situation where the backslope drains directly into the stream because the footslope has eroded away. Similarly, structural modification of the drainage in a field (terraces or grassed waterways) can lead to a different sequence of landscape positions. It is hypothesized that significant differences in runoff and agrichemical concentrations will occur at the outlet of a landscape because of the variations in the sequence of landscape positions. These effects will also be different when different lengths of landscape positions occur.

It is difficult to experimentally investigate the above proposition in natural settings and in a controlled environment where parameters other than those associated with landscape position, i.e.: management, soil type, precipitation, would be similar. Simulation models are one way to overcome these limitations. Models provide the flexibility of simulating different landscape arrangements and of comparing the output over time. In this study, the Agricultural Policy/Environmental eXtender (APEX; Williams et al., 2008) was used to simulate runoff and atrazine loss from 189 m long plots that are typical of claypan landscapes. APEX is a field/watershed scale model that provides flexibility to define weather, landuse, soils, topography, and management practices such as tillage, crop rotation, and agriculture inputs. The model can also take into account the impact of different configurations of management on erosion, water quantity and quality, soil quality, while allowing for routing processes for runoff, sediments, nutrients and herbicides/pesticides within and from fields (Saleh et al., 2004; Wang et al., 2006). APEX evaluates all these processes across complex landscapes through the channel to small watershed or field outlets (Srivastava et al., 2007). Gassman et al. (2010) reviewed many APEX simulation studies for different environments with various agricultural management practices to simulate runoff, herbicides and nutrients inside and at the outlet of watersheds. In all the studies, APEX was able to simulate different agricultural processes satisfactorily.

The goal of this simulation study was to evaluate the effects of landscape position on runoff and atrazine loss on claypan soils. Specific objectives were to: 1) test whether APEX is sensitive to variations of soil properties because of landscape position, and 2) determine the effects of the sequence and size of landscape positions with their corresponding slope and soil properties on the amount and intensity of simulated runoff and dissolved atrazine losses from claypan soils.

Materials and Methodology

Study Area and Cropping Systems

The study area is located in the Goodwater Creek Experimental Watershed (GCEW), a 7250 ha agricultural area in north-central Missouri. The area is characterized by a 30-year average annual precipitation of 964 mm and average annual minimum and maximum daily temperatures of 6.3 and 16.9°C, respectively. Thirty research plots, 189 x 18 m^2 dimension (figure 4.1), were laid out in 1991 in the south east headwaters of the GCEW to evaluate the effects of cropping systems on yield and transport of agrichemicals to surface water (Ghidey et al., 2005). These plots were hydrologically separated by berms to avoid the inter-mixing of surface flow and vertical plastic lining was inserted along the berm length to prevent subsurface flow between plots. The plot sites are on a sloping landscape (slopes ranging between 0 and 3%) with three major landscape positions: summit, backslope and footslope. The lengths of each landscape position varied from plot to plot. Generally the footslope was found to be shortest in all the plots and ranged from 18 to 33 m among three landscape positions. Summit and backslope positions were almost equivalent in length and ranged from 30 to 52 m and 24 to 55 m, respectively, for all the plots.

The predominant soils in the GCEW watershed are claypan soils (93%) of the Central Claypan Soil Major Land Resource Area (MLRA 113), an area of about 3 million ha in Missouri and Illinois (U.S. Department of Agriculture, Natural Resources Conservation Service, 2006; Lerch et al., 2005). Claypan soils have a dense and very slowly permeable layer generally occurring 15 to 45 cm below the surface and having much higher clay content than the overlying material. Claypan soils impart a unique hydrology by impeding the vertical flow of water and thus increasing surface runoff (Kitchen et al., 1999; Jung et al., 2005). The soils within the plots for this study are primarily classified as Mexico (fine, smectitic, mesic Aeric Vertic Epiaqualfs) and Adco (fine, smectitic, mesic Vertic Albaqualfs), which have the characteristic argillic horizon with clay content > 500 g kg^{-1} and have considerable quantity of smectitic clay minerals with high shrink-swell potential. These claypan soils can have crack volumes ranging around 0.06 m^3 m^{-3} due to high shrinkage during dry summers (Baer and Anderson, 1997; Jung et al., 2005).

Out of the thirty plots, six plots per year with three different tillage and herbicide management sequences were selected for measurement of surface runoff during the corn year of the rotation from 1997 to 2002. Overall, twelve plots were selected for the present simulation study; four plots under cropping system 1 (CS1), a mulch tillage corn/soybean rotation system; four plots under cropping system 2 (CS2), a no-till corn/soybean rotation; and four plots under cropping system 3 (CS5), a no-till corn/soybean/wheat rotation. For the third cropping system (CS5), an adaptive weed management practice was followed for which the herbicide type, rate, and timing were specific to weed intensity and species (Ghidey et al., 2005). Since the corn year of these plots was monitored from 1997 to 2002, runoff and dissolved herbicide data were available for each plot only for 2 to 3 years depending on the length of the rotation (table 4.1).

The twelve plots represented the three cropping systems with four plots in each. For each cropping system, two plots had the corn crop one year and the other two plots the next year. These plots with similar cropping system and similar cropping years were treated as replicates during the statistical analysis. Thus, for each cropping system, there were two sets of replicates.

Runoff Measurement and Sample Analysis

In 1996, the outlets of the selected plots were instrumented with ASTM-standard Parshall flumes (Culverts and Industrial Supply Co., Mills, WY) with nominal 0.154 m throat to measure the runoff amount on an event basis. Head was measured by a pressure sensor (America Sigma, Inc., New York, NY) for the calculation of total discharge for each event. A flow-proportioning sampler (Sigma 900MAX, America Sigma, Inc., New York, NY) with an 8 bottle rack was installed near the stilling well and connected to the sensor. Each bottle sampled up to 6.35 mm of runoff, which enabled the sampling of a maximum 50 mm total runoff depth. Collected runoff samples were analyzed for atrazine concentrations (Ghidey et al., 2005).

APEX Model Setup and Input Parameters

Due to the presence of a shallow claypan in the study area and low permeability of the soils, surface runoff was the major component of the hydrology. APEX includes two possible methods for estimating runoff volume – a modification of the Natural Resources Conservation Service (NRCS) curve number technique (U.S. Department of Agriculture-NRCS, 2004) and the Green and Ampt infiltration equation (Green and Ampt, 1911). The curve number method was used because it easily relates runoff to soil type, land use, and management practices (Williams et al., 2006).

The model was set up for each plot from 1997 to 2002, the period during which runoff was monitored and samples were collected and analyzed. The major inputs required for the model were soil parameters, weather, site conditions, cropping systems, and field management. An automated weather station was installed near the plots in 1991 (figure 4.1) with confirm data starting in 1993, from which sub-daily rainfall (mm), temperature (°C), average solar radiation (MJ m^{-2}), and wind speed (mm h^{-1}) data were collected, recorded and maintained in a server database managed by the Cropping Systems & Water Quality Research Unit (CSWQRU) at the University of Missouri-Columbia (Sadler et al., 2006).

Each plot's cropping and management system was outlined by Ghidey et al. (2005). Protocols were developed each year by the USDA-ARS-CSWQRU in Columbia, MO. Soil data measured on the plots were obtained from Dr. N. R. Kitchen (soil scientist, ARS-CSWQRU, March 2007, personal communication) for the soil samples collected from four landscape positions in nine plots out of thirty. The landscape positions included summit, backslope, footslope, and the shoulder, which is the transition between the summit and the backslope. Properties measured included texture, cation exchange capacity, organic carbon content, sum of bases, and pH for 4 to 6 horizons in each profile. Plots with missing soil data were assigned the data of plots having similar management and located nearest to the plot of interest. Soil physical parameters (vertical saturated hydraulic conductivity, Ksat; field capacity; bulk density) were measured by Jiang et al. (2007). They collected soil samples for three depths at 10-cm intervals for all landscape positions per plot except for the footslope where an additional depth of 30 to 40 cm was also included. To minimize the variability in soil physical parameters, average values were used for the same management, landscape position, and depth. For more details on soil properties, see Jiang et al. (2007).

The measured values of Ksat by Jiang et al. (2007) were the vertical Ksat, but in the present simulation study these values were also considered as horizontal Ksat. Mudgal et al. (2010) found in a study in a similar area, that the horizontal and vertical Ksat values were almost equivalent. In another study by Blanco-Canqui et al. (2002) in similar soils, they also found no significant differences between horizontal and vertical Ksat values.

A detailed elevation contour map of the study area is available in Kitchen et al. (1998). Elevation difference between the summit and plot outlet was about 2 m, with maximum slope at the backslope position, for all of the plots. Between summit and backslope, a transition zone was also delineated, i.e. a slight convex shoulder (Myers et al., 2007). Similarly a transition between backslope and footslope was also delineated, with 0 to 2% slope.

Once data sets were established, separate files for each plot were created. Each plot was divided into five landscape positions, specifically summit, transition between summit and backslope, backslope, transition between backslope and footslope, and footslope. The lengths of three main landscape positions ranged as follows: summit, 31 to 52 m; backslope, 25 to 55 m; and footslope, 18 to 33 m. For most plots, the backslope was the longest and the footslope the shortest.

Model Calibration

A manual sensitivity analysis was conducted for three plots, one from each cropping system, to identify sensitive parameters. Most APEX parameters incorporated in this sensitivity analysis were previously analyzed by Wang et al. (2006). A few other parameters were also considered: the selection of the method to estimate the curve number out of four possible choices and their corresponding parameters, the selection of potential evapotranspiration (PET) estimation method out of five different methods provided in APEX and the corresponding parameters, and all control parameters related to soil moisture content and pesticide movement. Main soil parameters were not considered during calibration and validation because measured values were available, but some of them were tested for sensitivity analysis. Jiang et al. (2007), in a study at the same site, found significant differences in depth to claypan, Ksat and bulk density for different landscapes. Therefore it was speculated these properties could explain the variations in runoff generation and atrazine loss from different landscape positions. Hence model sensitivity for these soil parameters was also tested. As stated before no difference was considered between horizontal and vertical Ksat values, therefore during the sensitivity analysis, both parameters were tested by varying them together. Single parameter sensitivity analysis was done by varying one parameter at a time from their maximum to minimum values and recording the subsequent changes in runoff and atrazine concentrations at the plot outlets.

The APEX model was calibrated and validated separately for each of the twelve plots. Since each plot was calibrated separately, values of some parameters were slightly different among plots. The parameters were adjusted to calibrate surface runoff, crop yield, and then atrazine concentrations in runoff. Other than soil, management, weather and topographic data, the model was started with default values of parameters provided in the model.

Calibration of the model was done on an event basis for runoff and dissolved atrazine concentrations. The calibration and validation periods were selected to have a comparable number of events in each: 1997 to 1999 for calibration and 2000 to 2002 for validation.

The model's goodness of fit was evaluated through the linear regression (r^2) method and the Nash and Sutcliffe (1970) efficiency equation:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_m - Q_s)^2}{\sum_{i=1}^{n}(Q_m - Q_a)^2} \qquad (1)$$

where NSE is the efficiency of the model, Q_m are measured values, Q_s are simulated values, Q_a is the average measured value, and n is the number of events. The r^2 method measures the correlation between measured and simulated values. The Nash and Sutcliffe equation measures how simulated values match the observed data. If NSE is close to 0.0 then model simulation is no more accurate than the mean of the observed data; if it is 1, simulation is considered perfect. Moriasi et al. (2007) recommend that NSE be greater than 0.5 and 0.7 for satisfactory and good calibration, respectively, at a monthly time step and note that it may need to be relaxed for daily time step calibrations. These authors also indicate that values of r^2 greater than 0.5 are often considered acceptable. However, they cautioned the use of r^2 because of its sensitivity to high values. Krause et al. (2005) suggested that when the r^2 efficiency criteria is considered, one should additionally use the slope and intercept values of the line of fit. Intercept should be zero and slope value should be close to 1 for a good agreement between simulated and measured values. Slopes greater and lower than 1 indicate over- and under-estimation, respectively, only when the intercept is close to zero.

Many researchers have considered various acceptable ranges for r^2 and NSE based upon the amount of available measured data, output time interval, and purpose of the study. Ramanarayanan et al. (1997) have taken $r^2 > 0.5$ and $NSE > 0.40$ as satisfactory values for the APEX model while studying surface water quality for daily events. Wang et al. (2007) suggested values of r^2 > 0.5 and NSE >0.40 as acceptable for monthly outputs of streamflow, nutrient concentrations, and runoff using the APEX model. Also, Santhi et al. (2001) found r^2 > 0.5 and NSE > 0.5 as acceptable values for monthly calibration values using the Soil and Water Assessment Tool (SWAT), a watershed-scale model that is very similar to APEX. In this study, r^2 > 0.5 and NSE > 0.45 were selected as thresholds for satisfactory calibration and validation, with regression between measured and simulated values having slope and intercept close to 1 and 0, respectively.

Landscape Sequence and Size

After the calibration and validation of the model, simulations were conducted to predict the effects on runoff and dissolved atrazine concentrations for two different types of landscape variations: (1) varying the sequence of landscape positions; and (2) varying the size of landscape positions. For the first type of landscape variation, six permutations of the sequence of landscape positions were considered. The natural sequence (summit-backslope-footslope) was the baseline sequence to which others were compared. Five theoretical sequences were developed and are shown in table 4.2. For the purpose of evaluating the sensitivity of the model to these permutations, we considered all the theoretical sequences, independently of their likelihood of occurrence. The profiles and soil properties of the transition zones were adapted to fit each theoretical sequence. Simulations were performed with the calibrated model separately for each plot and each sequence, with measured weather data from 1978 to 2007. The collection of measured climate data at the research plot site was initiated in 1993. Therefore, rainfall data measured at the nearest available rain gauge (figure 4.1) was used for the 1978 to 1992 precipitation inputs to the model, while the remaining climate data inputs were generated in APEX during that period. There were six simulations per plot, which were compared for seasonal runoff and atrazine loads from May to October at the plot outlet, as affected by landscape sequence.

For the second type of landscape variation, three scenarios were planned using the natural sequence of landscape positions. In each scenario, the length of one out of three landscape positions was increased by 20 % while maintaining the lengths of the others. The percent slope for all the landscape positions was left unchanged. Three simulations were conducted with the calibrated model independently for each plot, one for each size of landscape position, from 1978 to 2007, using measured weather data. The three simulations were then compared for seasonal runoff and atrazine loads during the cropping season at the plot outlet as affected by the size of each landscape position for the three cropping systems.

Percent change in runoff and atrazine load relative to the natural landscape sequence or size was calculated for the five theoretical sequences and the three sizes. Statistical comparisons were made among the sequences or sizes using SAS (SAS institute, 1999) with the PROC GLM procedure. The sequence and size of the landscape positions were tested for significant effects on runoff and atrazine loads at the 95% confidence level ($P<0.05$).

Result and Discussion

Sensitivity Analysis

The most suitable method for runoff calculation was determined to be the nonlinear curve number estimation method weighted by soil water content. This method calculates the curve number based on water content in the soil profile. The Hargreaves equation was used to estimate potential evapotranspiration. These methods were selected because they gave the best results as compared to measured data.

The two soil parameters found to be significantly different across landscape positions by Jiang et al. (2007), the hydraulic conductivity (Ksat) and the depth to claypan, were also found to significantly affect the results of the APEX model. Thus, there was strong indication that the APEX model would be able to discriminate these landscape positions based on their potential to generate runoff and herbicide losses. Higher Ksat values and deeper clay pan reduced the amount of runoff generated and the atrazine loss. The model was not found to be sensitive for the measured range of values of bulk density.

Parameters found sensitive for estimating atrazine loads are presented in table 4.3. In this, the pesticide leaching ratio and pesticide loss coefficient are related to soil properties and partition the atrazine loss between that moving downwards with percolating water in the soil profile and what is moving with surface runoff. During calibration, these two parameters were allowed to be different among the plots based on the management whereas the atrazine half life in soil was considered similar for all plots. Its calibrated final value was found to be 30 days. The other parameters listed in table 4.3 were adjusted during the calibration of the model within the ranges recommended in the APEX manual (Steglich and Williams, 2008).

Model Calibration and Validation

The coefficient of determination (r^2) and NSE value ranges for each cropping system are shown in table 4.4, along with the range of number of events recorded on each plot during the corn phase and used for calibration and validation. The number of events varied by plot based on which year the plots were under corn (table 4.1). In all cases, the coefficients of determination and NSE values were greater than 0.5 and 0.42, respectively. The r^2 varied more than expected, ranging from 0.5 to 0.9 for different plots of the same cropping system. This may be due to the fact that the years of the corn phase were different for different plots.

The criterion determined by Moriasi et al. (2007) for flow calibration at the monthly time step is a minimum NSE of 0.5 and a maximum percent bias of 25%. These daily time step results for a small number of events on each plot are therefore quite strong. In all cases, the goodness of fit was lower when there were fewer events recorded, a possible indication that the model performed better under normal or wet conditions. This may explain why the r^2 and NSE values were slightly lower during the drier calibration period for which there were 5 to 8 events recorded on each plot compared to the wetter validation period for which there were 8 to 19 events.

As suggested by Krause et al. (2005), the slope of the line of fit value is indicative of the bias of simulated output relative to the measured. Figure 4.2 illustrates some linear regression results, better and worse, between measured and simulated values. In figure 4.2a, which illustrates runoff validation results from plot 11, the slope is 1.11 and the intercept is 1.1. With a slope close to 1 and an intercept close to zero, these values indicate no strong bias. In comparison, figure 4.2b shows the worst case scenario. It illustrates the calibration results for daily atrazine load from plot 18. In that case, r^2 and NSE were 0.57 and 0.48, respectively, percent bias was -51%, and the line of fit slope (0.63) and intercept (7.15) indicate a bias and an over-estimation of the low loads.

Overall, average NSE values for each cropping system varied from 0.55 to 0.77 for runoff and from 0.53 to 0.64 for atrazine loads. Average percent bias for each cropping system varied from -24% to -36% for runoff with an exception of -50% for CS1. For atrazine loads, percent bias varied from -17% to -38%. In spite of some poorer results on some of the plots, these results were quite satisfactory in comparison to other APEX studies compiled by Gassman et al. (2010). Saleh et al. (2004) found NSE values in the range of 0.74 to 0.88 for daily runoff measured over 35 to 108 events in nine forested watersheds in eastern Texas; no validation results were reported. Wang et al. (2008) calibrated and validated the APEX model for the 22.5 km^2 Shoal Creek watershed, Fort Hood, Texas and achieved r^2 and NSE values in the range of 0.60 to 0.77 and 0.33 to 0.74, respectively, for daily stream flow. Williams et al. (2006) obtained r^2 values of 0.72 to 0.73 for surface runoff in a study at a bison feedlot in North Dakota.

Landscape Sequence and Size

The effect of varying the landscape sequence from its natural order was very similar for all three cropping systems, as shown in tables 4.5 and 4.6 for runoff and area unit atrazine loss, respectively. The maximum runoff and atrazine loss occurred at the plot outlet when backslope conditions were found just before the outlet (i.e. FSB and SFB sequences, table 4.2) and were significantly different ($p < 0.0001$) from the natural sequence (i.e. SBF sequence, table 4.2). Any of the other sequences in which either the footslope or the summit positions were positioned just before the outlet did not consistently produce significantly different runoff or atrazine loss compared to the natural sequence. However, the sequence FBS, the complete reversal of the natural sequence, did produce significantly higher area unit atrazine loss than the natural sequence (SBF) for half of the plots in each treatment. The runoff values, although always higher for FBS than for SBF, were not significantly higher than any of the other sequences.

The relative difference between each sequence and the natural sequence was visualized for plot 19 of CS1 (figure 4.3), which shows that the sequence that generates more runoff and atrazine load remains higher for all the years, and the sequence generating the least also remained lowest for all years. The magnitude of the differences varies from year to year because of the corn - soybean rotation and the weather variability. Atrazine loss is shown only for alternate years as it was applied only during the corn cropping years. Increase in runoff when backslope conditions occurred near the outlet ranged from 20 to 80%. Increase in atrazine loss ranged from 20 to 70% as depicted in figure 4.3. This trend was similar for all other cropping systems and the maximum increase in runoff and atrazine loss among all plots was 86 and 80%, respectively.

These results could be attributed to the fact that during sensitivity analysis of the model the runoff generated was found to be sensitive to the saturated hydraulic conductivity (Ksat) of the soil and the depth to claypan. Both parameters varied significantly with landscape position. In a previous study, the variation in vertical Ksat with landscape position was found significant in all the plots (Jiang et al., 2007), with the highest surface Ksat at the footslope and lowest at the backslope. Ksat values of the surface layer were on average 5 mm hr^{-1} for the footslope positions while they were only 0.43 mm hr^{-1} for the backslope. In addition, the depth to claypan was least at the backslope (7 to 17 cm) and largest at the footslope (21 to 70 cm) (Kitchen et al., 1998). Thus, the backslope was where runoff was first generated due to the lower permeability of the surface layer and the smaller water holding capacity caused by a shallow depth to claypan. The lower conductivity of the surface layer also impacted the ability of that layer to drain through lateral subsurface flow. This lower permeability resulted in higher values of the curve number, which increased the occurrence and magnitude of simulated runoff. It also decreased the percolation out of that surface layer, which together with a shallow depth to claypan, increased the surface layer water content, and caused an increase in the daily value of the curve number and in runoff. During a rainfall event, when the backslope was at the end of the sequence, water coming from the upper part of the landscape directly flowed out of the plot and hence increased runoff and dissolved atrazine loss. But when the footslope was at the end, its thicker and more permeable silt loam layer above the claypan acted as a buffer by allowing runoff and dissolved atrazine to infiltrate rather than to flow laterally. In that case, the runoff and atrazine load at the outlet of the landscape were lower. When the summit was located at the outlet, the runoff and atrazine load generated were in between the two extremes. These results were expected as the claypan thickness and Ksat values of the summit position were also in between those of the footslope and backslope positions.

Significant changes in the frequency of runoff occurrence for the landscape sequences were also found. The percentage of runoff days occurring relative to the occurrence of precipitation days (% RO) during a season was calculated by dividing the total number of runoff days by the total number of rainfall days during one season. As figure 4.4 shows, the highest % RO was for the FSB sequence almost for every year and the lowest for the BSF sequence. An increase in runoff events means more vulnerability to atrazine transport with runoff from the plots. There were 10% more runoff-causing precipitation events for the sequence that produced the most runoff events compared to the sequence that produced the least for the annual average of the total simulation period.

Tables 4.7 and 4.8 show the seasonal percent change in runoff and atrazine load with modified lengths of the landscape positions. The general trend was found to be similar within each cropping system during all the years (figure 4.5). The highest increase in runoff and atrazine load at the plot outlet occurred when the backslope position was increased by 20%. No difference occurred in runoff when the footslope position was lengthened.

Statistical analysis showed that runoff and atrazine loss at the plot outlet were significantly increased with the increase in the backslope lengths. The reduction in runoff and atrazine loss observed with an increase in the footslope was not statistically significant. The increase in the length of the summit position showed a different trend; in each treatment, two plots had a significant increase in runoff and atrazine loss in comparison to the control, and two had a non-significant increase.

Figure 4.5 shows the relative increase in runoff and atrazine load with the change in different landscape sizes for plot 19 of cropping system 1, and the trend is similar for all the plots under all cropping systems. The largest increases in runoff and atrazine area unit loss were obtained when the length of the backslope was increased by 20%. This indicates that a longer backslope, even when buffered by a footslope, could have damaging effects in terms of increased runoff and atrazine load. Therefore priority has to be given to treat the longer backslope first. The maximum relative increase in runoff and atrazine load among all the plots due to backslope increase was 83 and 72%, respectively, and the average relative increases were 33 and 42%, respectively.

The difference in runoff and atrazine load due to landscape size increase could also be attributed to the fact that the lengths of the landscape positions were increased by 20 percent of the original length. With the backslope being the longest for all the plots and the footslope position the shortest, the 20 percent increase in the length resulted in a larger lengthening of the backslope than the footslope position. An alternate explanation may be that the length of the footslope does not significantly affect the runoff or atrazine load. To test these possible explanations, the model was run from 1997 to 2002 and the footslope length was increased by increments of 3, 5, and 10 m, and the original footslope lengths for all the plots ranged from 18 to 33 m. No significant difference was found for runoff and atrazine load between control and landscape with increased footslope length. While this supports the possibility that lengthening the footslope does not significantly change runoff and atrazine loadings as long as there is a footslope, further investigations need to confirm this.

Implications

All the results from the present study point out conclusively that in the claypan region a landscape sequence with shallower clay depth (as in backslope position) near the outlet would generate more runoff and atrazine load. Similarly, a longer landscape with shallower claypan depth would be prone to generate more runoff and atrazine load. On the other hand, if clay was deeper in the profile near the outlet it would reduce the runoff and atrazine load at the outlet. These results have significant implications for management. Instead of treating and managing fields uniformly, the areas with shallower clay depth could be treated as critical areas and could be managed separately to minimize ill impacts on downstream regions.

These results have implications regarding the impacts of natural or man-made changes that occur in the landscape. For example, stream bank erosion can impact water quality in more than one way. While the direct consequence is the loss of large amounts of soil into the stream, secondary effects are expected if erosion is severe enough to affect the footslope of the landscape sequence. In that case, the resulting sequence would be one with a reduced footslope length. In the extreme case of total disappearance of the footslope, the resulting landscape sequence would end with a backslope. In this case, runoff and chemical losses from the agricultural landscape would increase and could be significantly larger. The severity of the increase in losses will depend on the length of the backslope and summit. Similarly, while the construction of terraces is an effective way to reduce soil erosion on steep slopes, it could have additional effects on runoff and the transport of atrazine because the length of the back slope is reduced, thus decreasing runoff and atrazine losses. On the other hand, terraces are placed in the middle of the landscape, usually within the backslope position. Thus water and pollutants drain directly into these structures without going through and getting the benefit of a footslope with deeper depth to clay. In addition, the broad-based terraces that are frequently found in this region are built by removing some top soil, excavating the uphill area of the terrace to build the berm, and placing the topsoil back on top of the berm and excavated area. Thus, the area of farmed land directly uphill of the berm ends up having a steeper slope and lower depth to clay than the original backslope. Hydraulic conductivity would depend on the final compaction of the soil. Consequently, this area becomes more sensitive than the original landscape profile, which may offset the terrace's benefits with regard to runoff and atrazine losses.

In this study we benefitted from a very detailed description of landscape topography, soil properties and the depth to claypan. While GIS and soil information are tools frequently used by researchers, this level of information is normally out of reach for farmers. Nevertheless topographic information and SSURGO soil maps are available to delineate the critical areas based on landscape type. Additional research is needed to test whether similar results could be obtained based on readily available data in this region. If so, one can envision a landscape position dependent management in which these critical areas would benefit from crop rotations and management practices that would take the shallow depth to claypan into account.

Simulation models are important tools not only for research purposes but are also extensively needed to develop specific management principles applicable on targeted locations. There are many models available at various scales but each comes with their own limitations (Singh et al., 1995). In the present study, we showed that APEX, a daily time step model, could be used at the landscape scale and was detailed enough to detect the effect of the different landscape positions. In particular, soil parameters specific to the backslope position, i.e. hydraulic conductivity, slope, and depth to claypan, significantly affected simulated runoff and atrazine loss at the outlet. On the other hand, we did not find that APEX was sensitive to the soil bulk density in the range of values that distinguish the different positions of a claypan landscape. The theoretical landscape sequences generated were an effort to stretch the limits of the APEX model to test whether simulated runoff and atrazine loss were sensitive to the differences in slope and soil properties inherent to different positions along the landscape. We recognize that these sequences are theoretical and some of them are unlikely to occur. Results indicate that this model is indeed sensitive to landscape positions and their associated soil properties and thus can be used to define and test management scenarios (cropping systems, crop rotations, tillage and inputs) adapted to each position.

Conclusion

This study was conducted to evaluate variations in simulated runoff and dissolved atrazine load at the plot outlet of a claypan landscape due to different landscape sequences and sizes for claypan soils. This research demonstrated that the calibrated and validated model APEX was able to produce the differences in simulated runoff and atrazine load associated with different sequences of landscape positions and with different lengths of landscape positions.

APEX model was able to simulate runoff and atrazine loss from agricultural plots in a claypan area as indicated by the selected goodness of fit criteria. For daily runoff, r^2 and NSE varied between 0.55 – 0.98 and 0.46 – 0.94, respectively; for daily atrazine loads, r^2 and NSE values ranged between 0.52 – 0.97 and 0.45 – 0.86, respectively. The slopes of the regression between measured and simulated values varied between 0.70 and 1.38.

Landscape sequence analysis showed that the sequences ending with a backslope produced the most runoff and atrazine loss. The Footslope-Summit-Backslope (FSB) sequence produced the highest amount of seasonal runoff and atrazine loads, 86 and 82% more, respectively, than the natural Summit-Backslope-Footslope (SBF) sequence. Seasonal runoff and atrazine loads were highest and increased significantly by 83 and 72%, respectively, when the backslope length was increased by 20% relative to its original length. These findings may be helpful in delineating critical areas for conservation management within fields. These theoretical landscape sequences may not occur naturally, but these results can be useful to take landscape characteristics into account for management decisions. For example, if a crop field is large enough to accommodate different management systems, the areas that have longer backslope positions need extra effort to reduce runoff and atrazine loads. Efforts are especially needed when these landscape characteristics occur near the outlet, channel, or any subsurface drainage system.

In this study, the critical characteristics that separated the summit, backslope, and footslope positions from each other were the landscape geometries (slope and length), depth to claypan, and hydraulic conductivity above the claypan. The latter two parameters were also found sensitive in the APEX model for runoff and atrazine load estimation. These findings could allow land managers and conservationists to delineate critical areas based on depth to claypan and saturated hydraulic conductivity and to test alternative management systems for these areas with the APEX model.

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Tables

Table 4. 1: Research plots under corn management with respective treatments, by year. CS1: mulch tillage corn/soybean rotation system; CS2: no-till corn/soybean rotation; and CS5: no-till corn/soybean/wheat rotation.

Year	Plot Nos.	Cropping System
1997	19, 22	CS1
	13, 24	CS2
	8, 16	CS5
1998	11, 23	CS1
	18, 21	CS2
	20, 25	CS5
1999	19, 22	CS1
	13, 24	CS2
2000	11, 23	CS1
	18, 21	CS2
	8, 16	CS5
2001	19, 22	CS1
	13, 24	CS2
	20, 25	CS5
2002	11, 23	CS1
	18, 21	CS2

Table 4. 2: Theoretical sequence of landscape positions with abbreviations.

Landscape Sequence	Upper Position	Transition Zone (TZ)	Middle Position	Transition Zone (TZ)	Lower Position
Theoretical Sequence					
SFB	Summit		Footslope		Backslope
FSB	Footslope		Summit		Backslope
FBS	Footslope		Backslope		Summit
BFS	Backslope		Footslope		Summit
BSF	Backslope		Summit		Footslope
Original sequence					
SBF	Summit		Backslope		Footslope

Table 4. 3: Parameters considered for calibration of the model (for detailed description of parameters, see Williams et. al., 2008).

Input File	Parameter (abbreviation)	Description	Range of Values	Calibrated Values*
Parm	PARM3 (WSHI)	Water-Stress Harvest Index	0.0 – 1.0	0.7
	PARM5 (SWLL)	Soil water lower limit in the top 0.5 m soil	0.0 – 1.0	0.7 – 0.8
	PARM16 (ECRP)	Expands CN Retention Parameter (1.0 – 1.5)	1.0 – 1.5	1.1 – 1.3
	PARM17 (SEPC)	Soil Evaporation Plant Cover Factor	.01 – 0.5	0.3
	PARM24 (PLR)	Pesticide Leaching Ratio	0.1 – 1.0	0.1 - 0.2
	PARM34 (HPETE)	Hargreaves PET Equation Exponent	0.5 – 0.6	0.6
	PARM38 (WSEC)	Water Stress Weighting Coefficient	0.0 – 1.0	0.5 -0.6
	PARM42 (CNIC)	NRCS Curve Number Index Coefficient	0.3 – 2.5	0.8 -1.2
	PARM44 (UCNRP)	Upper limit of Curve Number Retention Parameter	1.0 – 2.0	1.3 – 1.6
	PARM63 (PLC)	Pesticide Loss Coefficient	0.1 – 1.0	0.15 – 0.25
Pest	PHLS	Pesticide Half Life in Soils (days)	10 - 100	30

* Range of values is provided if different values were used for different plots.

Table 4. 4: Range of r^2 and NSE values and total number of runoff events recorded during calibration and validation periods for all the plots under different cropping systems; CS1: a mulch tillage corn/soybean rotation system; CS2: a no-till corn/soybean rotation; and CS5: a no-till corn/soybean/wheat rotation.

Cropping system	Calibration (1997 to 1999)						
	Runoff			Atrazine loads			Number of runoff events recorded during the corn phase
	r^2	NSE	PBIAS	r^2	NSE	PBIAS	
CS1	0.58 – 0.93	0.49 – 0.61	-51% to -24%	0.52 – 0.89	0.46 – 0.65	-53% to -3%	7 – 8
CS2	0.60 – 0.90	0.47 – 0.65	-49% to -18%	0.52 – 0.92	0.46 – 0.68	-51% to -15%	5 – 7
CS5	0.76 – 0.92	0.46 – 0.67	-59% to -32%	0.53 – 0.89	0.48 – 0.73	-25% to -13%	5 – 8
	Validation Period (2000 to 2002)						
CS1	0.65 – 0.98	0.59 – 0.94	-39% to -12%	0.60 – 0.97	0.49 – 0.86	-26% to -6%	13 – 19
CS2	0.71 – 0.92	0.52 – 0.89	-34% to -12%	0.52 – 0.86	0.46 – 0.77	-41% to -2%	6 – 16
CS5	0.65 – 0.95	0.58 – 0.92	-51% to -13%	0.58 – 0.93	0.42 – 0.80	-34% to -4%	12 – 19

Table 4. 5: Effects of landscape sequence on 30-year average annual runoff on plots with different management; CS1: a mulch tillage corn/soybean rotation system; CS2: a no-till corn/soybean rotation; and CS5: a no-till corn/soybean/wheat rotation.

Landscape Sequence[$]	Simulated Average Annual Runoff (mm)											
	CS1				CS2				CS5			
	I*		II*		I		II		I		II	
SBF	176	c[#]	177	b	178	b	178	b	183	b	187	b
FSB	250	a	246	a	251	a	254	a	262	a	269	a
SFB	229	ab	229	a	234	a	236	a	241	a	245	a
FBS	216	abc	213	ab	215	ab	215	ab	221	ab	225	ab
BFS	183	c	181	b	182	b	183	b	189	b	194	b
BSF	172	c	168	b	168	b	168	b	177	b	179	b

* The plots under corn crop during same year are grouped together to calculate the means, giving two different groups in each treatment, I and II.

Within a column, sequences with the same letter are not significantly different at the 95% confidence level.

$ Where, S – Summit, B – Backslope, and F – Footslope.

Table 4. 6: Effects of landscape sequence on 30-year average annual area unit atrazine loss on plots with different management; CS1: a mulch tillage corn/soybean rotation system; CS2: a no-till corn/soybean rotation; and CS5: a no-till corn/soybean/wheat rotation.

Landscape Sequence	Simulated Average Annual Atrazine Loss (g/ha)											
	CS1				CS2				CS5			
	I*		II*		I		II		I		II	
SBF	38	bc#	32	c	46	d	47	bc	52	b	65	c
FSB	56	a	52	a	70	a	69	a	77	a	96	a
SFB	48	ab	44	b	62	ab	63	a	71	a	90	ab
FBS	45	bc	42	b	57	bc	59	ab	66	a	82	abc
BFS	39	bc	34	c	48	cd	48	bc	55	b	67	bc
BSF	35	c	30	c	44	d	44	c	51	b	63	c

* The plots under corn crop during same year are grouped to calculate the means that gives two different groups in each treatment, I and II.

Within a column, sequences with same letter are not significantly different at the 95% confidence level.

$ Where, S – Summit, B – Backslope, and F – Footslope.

Table 4. 7: Effects of the size of landscape position on 30-year average annual runoff on plots with different management; CS1: a mulch tillage corn/soybean rotation system; CS2: a no-till corn/soybean rotation; and CS5: a no-till corn/soybean/wheat rotation.

Scenario	Simulated Average Annual Runoff (mm)											
	CS1				CS2				CS5			
	I*		II*		I		II		I		II	
Increase in Backslope	245	a#	240	a	250	a	249	a	257	a	262	a
Increase in Summit	221	ab	221	a	223	ab	230	a	226	a	231	ab
Control	176	b	177	b	178	b	178	b	183	b	187	b
Increase in Footslope	172	b	175	b	176	b	175	b	179	b	183	b

* The plots under corn crop during same year are grouped to calculate the means.

Within a column, sequences with same letter are not significantly different at the 95% confidence level.

Table 4. 8: Effects of the size of landscape position on 30-year average annual area unit atrazine loss on plots with different management; CS1: a mulch tillage corn/soybean rotation system; CS2: a no-till corn/soybean rotation; and CS5: a no-till corn/soybean/wheat rotation.

Scenario	Simulated Average Annual Runoff (mm)											
	CS1				CS2				CS5			
	I*		II*		I		II		I		II	
Increase in Backslope	54	a	48	a	68	a	66	a	76	a	93	a
Increase in Summit	47	ab	41	a	58	ab	57	a	65	a	81	ab
Control	39	b	34	b	48	bc	47	b	52	b	65	b
Increase in Footslope	36	b	31	b	44	c	43	b	50	b	63	b

* The plots under corn crop during same year are grouped to calculate the means.
# Within a column, sequences with same letter are not significantly different at the 95% confidence level.

Figures

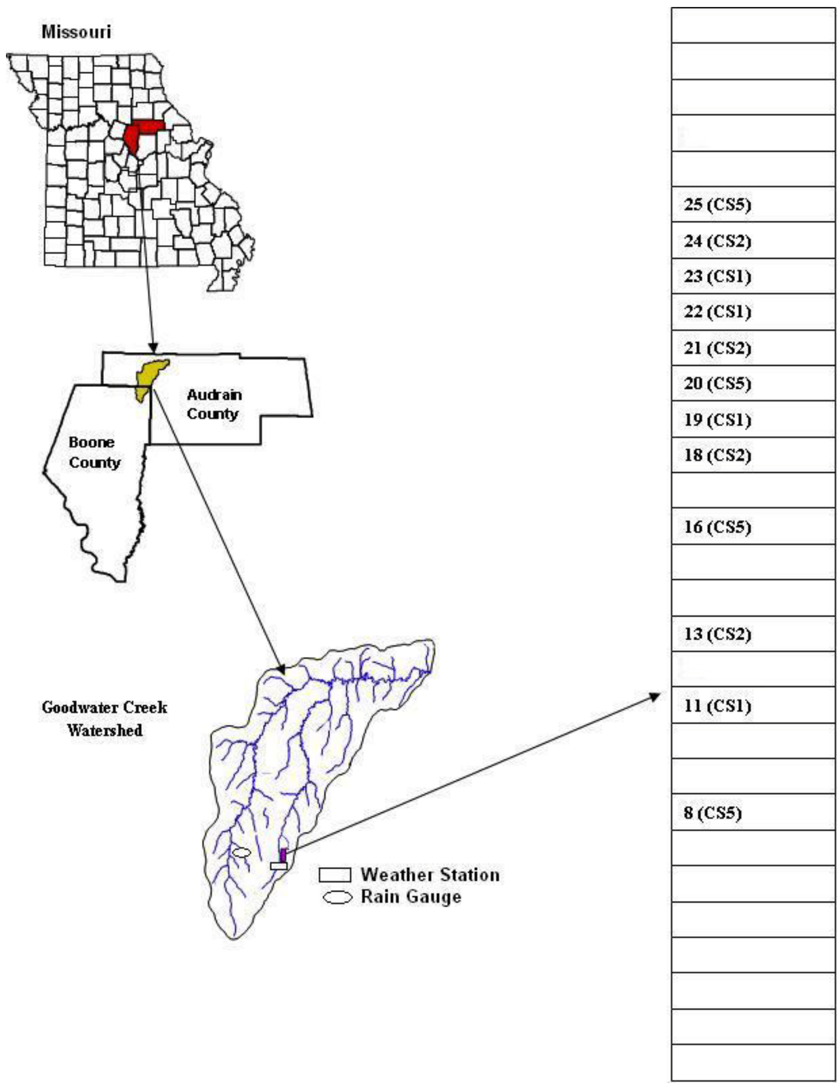
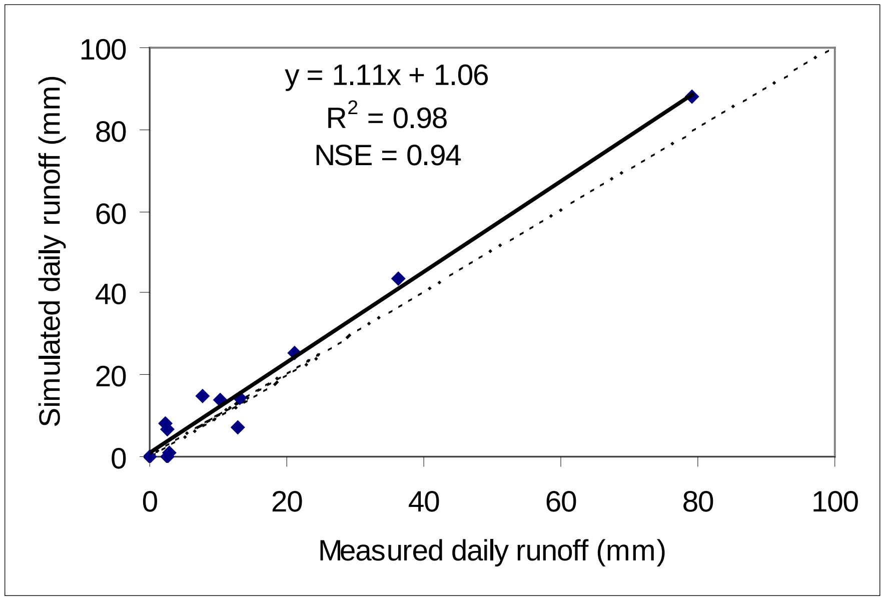
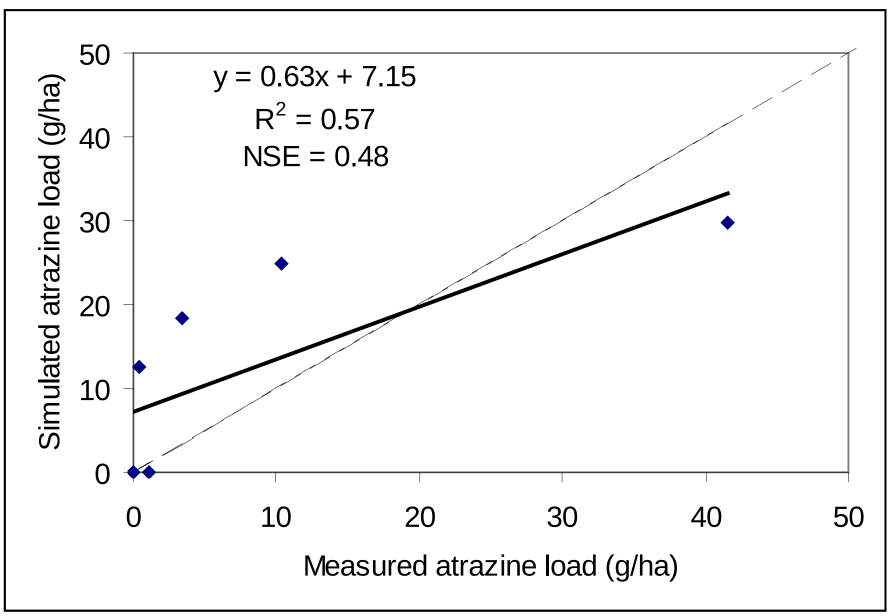


Figure 4. 1: Location of the twelve research plots, rain gauge, and weather stations with plot numbers and treatments used for the present study. CS1: a mulch tillage corn/soybean rotation system; CS2: a no-till corn/soybean rotation; and CS5: a no-till corn/soybean/wheat rotation (adapted from Ghidey et al., 2005).

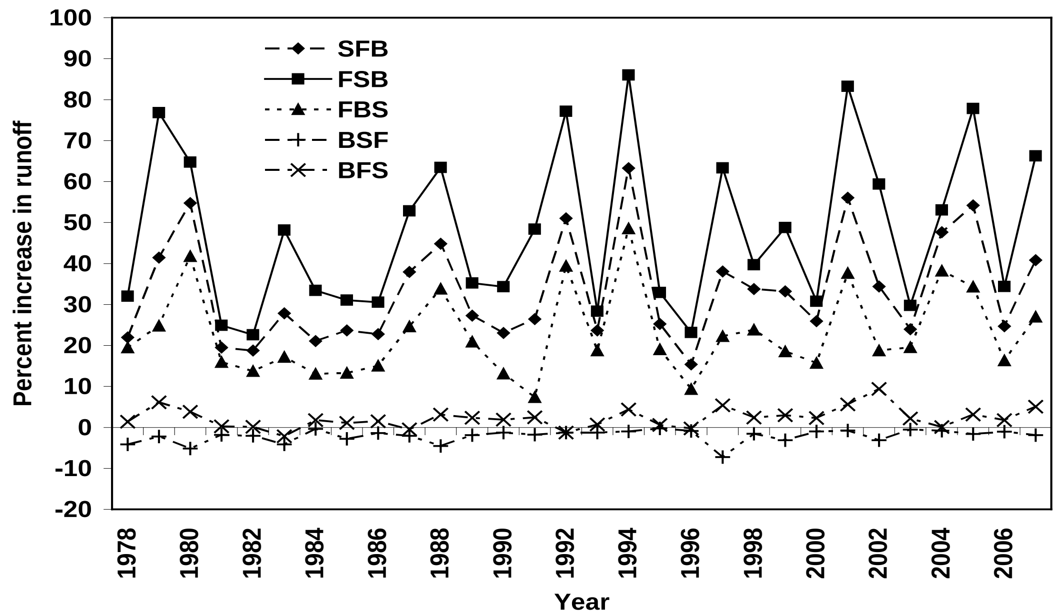


(a)

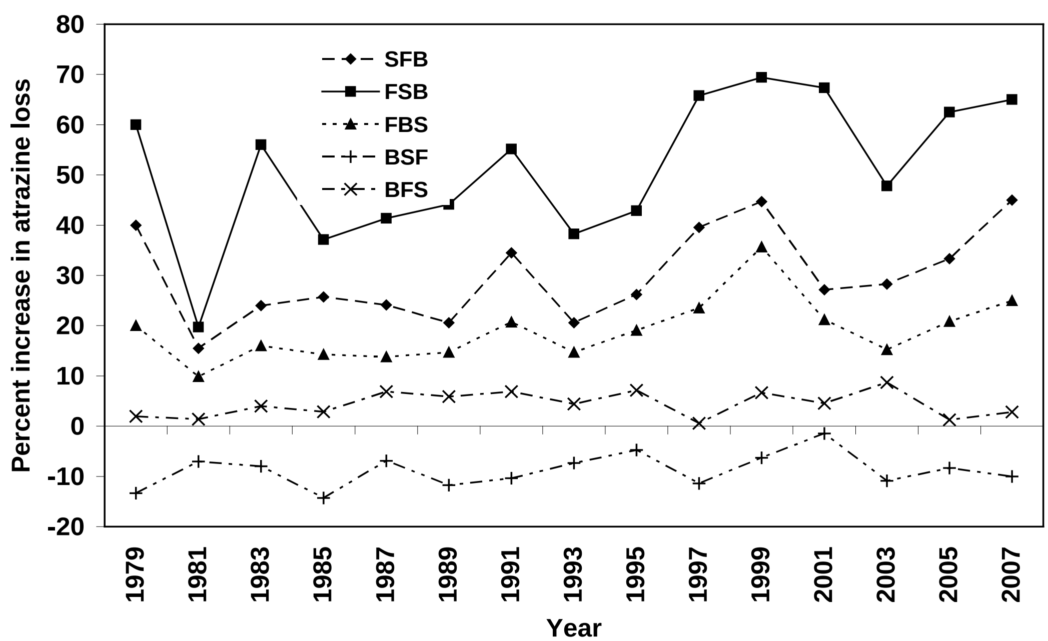


(b)

Figure 4. 2: Examples of linear regressions of measured vs. simulated values: a) daily runoff during validation period at plot 11, management CS1 (mulch tillage corn/soybean rotation system), b) daily atrazine load during calibration period at plot 18, management CS2 (no-till corn/soybean rotation system).



(a)



(b)

Figure 4. 3: Seasonal percent increase in (a) runoff (mm) and (b) atrazine loss ($g\ ha^{-1}$; only during corn cropping years) for the theoretical landscape sequences relative to the natural sequence (SBF), for crop management CS1: a mulch tillage corn/soybean rotation system, Plot 19.

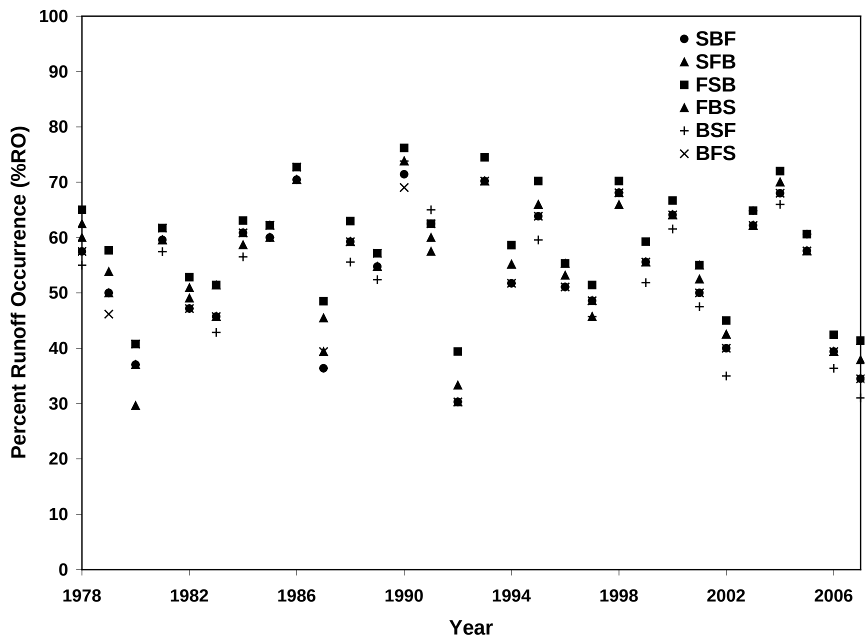
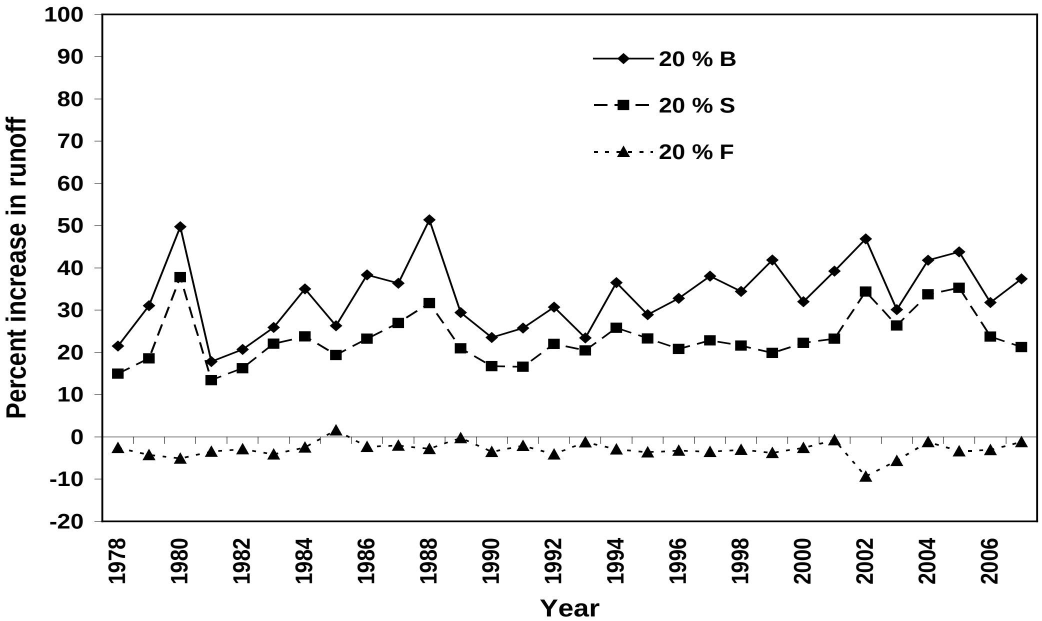
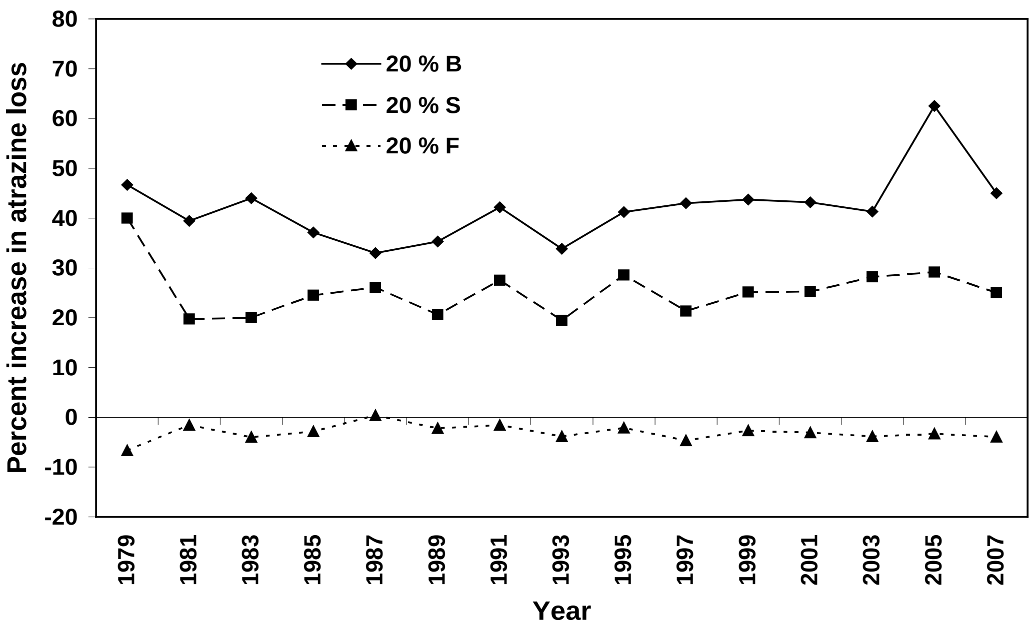


Figure 4. 4: Frequency of seasonal runoff occurrence (%RO) for five theoretical landscape sequences and one natural sequence from 1978 to 2007.



(a)



(b)

Figure 4. 5: Seasonal percent increase in (a) runoff (mm) and (b) atrazine loss (g ha^{-1}; only during corn cropping years) as influenced by increases in the length of specific landscape positions, for crop management CS1: a mulch tillage corn/soybean rotation system, Plot 19.

CHAPTER 5

ESTIMATION OF PARAMETERS FOR THE DELINEATION OF CRITICAL MANAGEMENT AREAS USING SIMULATION MODEL APEX IN CLAYPAN SOILS

Abstract

Targeting critical management areas (CMAs) within fields is essential to maximize cultivation area while implementing management practices to minimize impacts on water quality. The objective of this study was to develop a physically-based index to identify CMAs in a 32-ha field. The field was characterized by a claypan, a restrictive clay layer occurring within the upper 30 to 50 cm, and was under a corn-soybean crop rotation since 1991. At that time a V-notch weir was installed at the outlet for measurement of runoff, sediment and atrazine transport. Thirty-five subareas were defined based on slope, claypan depth, and soil mapping units. The Agricultural Policy/Environmental eXtender (APEX) model was calibrated and validated from 1993 to 2002 for runoff, sediment and atrazine loads. Simulated output by subarea was correlated with physical parameters including claypan depth (CD), surface saturated hydraulic conductivity (Ksat) and subarea slope (SL). Two indices were developed, the Conductivity Claypan Index (CCI; CD*Ksat /SL), and the Claypan Index (CPI; CD/SL) that correlated with runoff (r = -0.77), and atrazine and sediment loads (r = -0.55). These indices captured 100 % of CMAs for runoff and sediment yield and 75 % of CMAs for atrazine load, as predicted by APEX. These critical areas were also areas with lower productivity. Management scenarios were simulated that differentiated the management

of the CMAs from the rest of the field. Indices such as these for identifying areas of higher environmental risk and lower productivity could prove beneficial for effective implementation of best management practices.

Introduction

There have been many efforts and improvements to minimize the impact of non point source pollutants (NPS) on various water bodies. These efforts include placement or incorporation of different management practices. While working at small scales (e.g. plots) these practices demonstrate positive results in relation to the reduction of NPS, and improvement of localized soil fertility. At larger scales (e.g. watersheds or fields) many studies have shown non significant or very little improvement (Park et al., 1994; Inamdar et al., 2002; Simpson and Weammert, 2008; Meals et al., 2010). There are many factors that could diminish the impact of BMPs (Best Management Practices) at the watershed outlet such as: targeting non critical areas, hydrologic lag time (i.e. the time between the implementation of BMPs and the detectable changes to occur in water quality), number of BMPs, maintenance of BMPs, type of BMPs, etc. (Meals et al., 2010).

Delineation of Critical Management Areas (CMAs) would minimize one factor of uncertainty for better placement of BMPs. CMAs can be defined as the areas that require special attention because of high potential for surface runoff and non point source pollutants, possibly also leading to lower crop yields. Once the CMAs are delineated, they could be targeted as locations for BMP establishment. To be understood and appealing to local land managers, farmers, and stake holders, the delineation of CMAs should be based on easily available and physically measured parameters. Such parameters may include soil characteristics, topographic variables, management, upstream area, etc.

Walter et al., (2000) had found CMAs in the New York water supply watershed as the flat areas, particularly at the base of hill slopes. These areas were characterized by excessive lateral flow because upstream steep slopes have high infiltration capacity and a restrictive layer; as a result there was little runoff from these slopes but significant subsurface flow. As a result, the bottom flat areas became prone to saturation because of incoming subsurface flow and thus to runoff generation. The major runoff process was saturation excess flow (Hewlett and HIbbert, 1967). In contrast, the study in chapter 4 of this dissertation suggests that in the claypan region of Missouri, the middle part of a landscape was the most critical area for runoff generation and subsequently NPS transport. This was attributed to the presence of poorly drained shallow top soil with low hydraulic conductivity, over a restrictive high clay content layer known as a claypan. These different studies demonstrate that the location of these critical areas and the selection of the parameters that define them are dependent on the local hydrology, topography, soils, weather, and agricultural practices Therefore, parameters used for delineation of CMAs are likely to be location specific.

There have been a few indices developed for delineation of critical areas and for studying the hydrologic behavior of specific locations. Heathwaite et al., (2000) developed indices for targeting critical areas that generate and transport excess nutirents in a mixed management watershed located in Pennsylvania. They considered the proximity of an area to streams and the factors influencing saturation-excess runoff generation as the transportation factors. Fertilizer application method and rate, P and N levels in soils, and application method of organic fertilizer were considered source factors (Gburek et al., 2000). Based on the intensity of transportation and generation of N and/or

P at a location, the authors assigned a score to each factor and combined those to calculate a final score used to delineate critical source areas. They found that critical areas for P loadings were in close proximity to streams whereas a majority of critical areas for N loadings were on the outer boundaries of the watershed.

This type of approach for delineation of CMAs was more subjective whereas other methods such as the Topographic Wetness Index (TWI; Beven and Kirkby, 1979) and its many modified versions (Hjerdt et al., 2004; Ibbitt and Woods, 2004; Sorensen et al., 2005; Grabs et al., 2009) are more physically based. The TWI is calculated following equation (1):

$$TWI = \ln\left(As/\tan\beta\right) \tag{1}$$

where *As* is the specific catchment area and tan *β* is the slope.

TWI was previously used by Fraisse et al. (2001) in Missouri at the location of the present study for identifying management zones. These authors compared the variability of TWI, elevation, slope, and soil ECa (apparent soil electrical conductivity) as well as the variability of crop yields in an agricultural field and found that elevation and soil ECa better represent the crop yield variability in the field than TWI. Kitchen et al. (2005) confirmed their findings and concluded that productivity zones developed from the field's measured crop yield maps agreed with the management zones delineated using elevation and soil ECa data.

Simulation models have also been used for delineating areas critical for generating and transporting higher amounts of runoff and non point source pollutants. Young et al. (1989) used the AGricultural Non-Point Source Pollution model (AGNPS) for two watersheds in Winona and Big Stone counties in Minnesota. To apply this grid based model, they divided the watershed into 0.4-to 16-ha geographic cells. Areas generating higher sediments, nutrients (Total N and P), and runoff were classified as critical areas and were targeted for BMP installation. Endreny and Wood (2003) used an Export Coefficient Model (ECM) coupled with geographic information system (GIS) raster maps to delineate phosphorus critical loading areas in New York's West Branch Delaware River Watershed. A Contributing Area and Dispersal Area (CADA) weighing function was developed for predicting spatial patterns of phosphorous loadings; the CADA weighing function was based on landscape position, runon from upslope areas, and availability of trapping opportunities. They successfully classified these areas into three parts: 1) areas where pollutants were present, 2) areas vulnerable to pollutant transport with runoff, and 3) areas with likelihood of trapping pollutants using buffers. The resulting critical management areas generally matched what was observed in the field.

Srinivasan et al. (2005) compared two physically based models, the Soil and Water Assessment Tool (SWAT) and the Soil Moisture Distribution and Routing (SMDR) model for delineating critical source areas (similar to CMAs) for runoff generation and phosphorus transport. Busteed et al. (2009) used the SWAT model to target critical source areas generating higher amounts of sediment and phosphorous loads in the Wister Lake Basin, Oklahoma. They found that just 10% of the basin was generating 85% of the total pollution. Using that information, they were able to target specific agricultural producers and enroll them in their water quality program, thus optimizing limited cost share funds.

The delineation of CMAs should be based upon easily accessible physical parameters rather than based on complex and technical procedures that are more costly and time consuming (Wang and Cui, 2005). However, because of the complexity of delineating CMAs and their dependence upon many parameters, criteria are often simplified to an extent where they lose their primary purpose; therefore a balance is needed between ease of delineation and capturing the most critical areas (Line and Spooner, 1995).

In the present study area, which is characterized by claypan soils, Lerch et al. (2005) found that surface runoff was a main hydrologic process causing excessive losses of non point source pollutants (Lerch et al., 2005). In two separate studies, Ghidey et al. (1997) and Ghidey and Alberts (1999) concluded that in claypan soils, runoff events immediately following herbicide and/or fertilizer application were most risky for excessive losses of these constituents to the downstream area and water bodies. Therefore, it could be considered that runoff and the related non point source pollutant transport were the most important to be controlled in claypan soils for minimizing environmental hazardous impacts on downstream areas and water bodies.

The study in chapter 4 provided a background for the present study; namely that, in claypan soil landscapes, some landscapes positions were more prone to generating runoff and non point source pollutants. The backslope position, distinguished by a shallow depth to claypan (CD; 7 to 17 cm), low values of surface saturated hydraulic conductivity (Ksat; 0.43 mm hr^{-1} on average), and a steeper average slope (SL; 1.7% on average) in comparison to other landscape positions generated and transported higher amounts of runoff and atrazine loads. Hence the hypothesis for the present study was that these three physically based parameters, CD, Ksat, and SL, could be used for the delineation of CMAs in claypan soils generating higher amounts of runoff, sediment, atrazine, and dissolved nitrate and phosphorous.

Keeping the above hypothesis in mind, the study was done with two main objectives: 1. Delineate CMAs that generate disproportionate amount of runoff, sediment, atrazine, and dissolved nitrate and phosphorous, and 2. Identify physically based soil and land parameters responsible for runoff, sediment, atrazine, and dissolved nitrate and phosphorous generation to develop an index that could be used for CMA delineation in claypan soils.

Methodology

Study Area and Cropping System

The present study was done in a 32-ha agricultural field (Fig. 5.1) managed by the USDA-ARS Cropping System and Water Quality Research Unit (CSWQRU) in Columbia, MO. This field is located in the Goodwater Creek Experimental Watershed (GCEW), a 7250 ha agricultural area in north-central Missouri. The predominant soils in the watershed are claypan soils (fine, smectitic, mesic, Aeric Vertic Epiaqualfs and Vertic Albaqualfs). This watershed is part of the Central Claypan Soil Major Land Resource Area (MLRA 113), an area of about 3 million ha in Missouri and Illinois (USDA, NRCS, 2006; Lerch et al., 2005). Claypan soils have a dense, compact, slowly permeable layer generally occurring 20 to 40 cm below the surface and having much higher clay content than the overlying material (Lerch et al., 2005). This feature imparts a unique hydrology, by impeding the vertical flow of water and thus increasing the surface runoff (Kitchen et al., 1999; Jung et al., 2005). Average annual precipitation of area is 968 mm and average annual minimum and maximum daily temperatures are 6.3 and 16.9°C, respectively, based on 30 year period from 1978 to 2007.

Historically, this field was under corn, soybean, grain sorghum, and wheat crops with plow and disk tillage. After 1991, the field was under uniform management with a corn/soybean rotation with mulch tillage (Lerch et al., 2005).

Data Collection

Runoff Measurement and Sample Analysis

A v-notch weir was constructed at the field outlet (Fig. 5.1) in 1991 and was instrumented with a runoff water stage recorder and a refrigerated automated pumping sampler (ISCO 3230, Teledyne Isco, Inc., Lincoln, Nebraska). Threshold value for triggering the runoff sample collection was 0.8 mm and it continued to collect samples through the runoff event. Samples were then refrigerated, transported to the laboratory, and analyzed for atrazine [6-chloro-2-ethyl-4-(1-methylethyl)-1,3,5-triazine-2,4-diamine], dissolved nitrogen (NO_3-N), dissolved phosphorous (PO_4-P), and sediment. Details on the sampling and analysis methods were discussed in Lerch et al. (2005) and Ghidey et al. (2010). The data collected from 1993 to 2001 were used for the present study including daily runoff, sediment, atrazine, dissolved nitrogen, and dissolved phosphorous loads. An automated weather station was installed in the field in 1991 (Fig. 5.1) with confirmed data starting in 1993, from which hourly rainfall (mm), temperature (°C), average solar radiation (MJ m^{-2}), relative humidity (fraction), and wind speed (mm h^{-1}) data were collected, recorded and maintained in a server database managed by the USDA-ARS Cropping Systems & Water Quality Research Unit (CSWQRU) at the University of Missouri-Columbia (Sadler et al., 2006).

Soil, Elevation, and Crop Yield Data Collection

An order 1 soil survey (1:5,000 scale) was conducted in the field during 1993 and 1997 and the field was categorized into seven different soil series (Fig. 5.2). Soil properties including texture, cation exchange capacity, organic carbon content, sum of bases, and pH for 4 to 6 horizons in each soil profile were measured at nineteen points spread around the field. Soil hydraulic properties including saturated hydraulic conductivity (Ksat), bulk density, field capacity, and wilting point were recently measured at these points with detailed results shown in chapter 3. The major soil properties for each soil series are presented in Table 5.1.

Apparent electrical conductivity (ECa) is a relatively easy to measure, sensor based parameter in comparison to other soil physical and chemical properties. A Veris model 3100 sensor manufactured by Veris Technologies of Salina, Kansas and the EM38 manufactured by Geonics Limited, Mississauga, Ont., Canada (Sudduth et al., 2003) were used to measure ECa in the field. A detailed description of the methodology is given by Kitchen et al. (2005) and Sudduth et al. (2005). Sudduth et al. (2005) found ECa data highly correlated with the clay content of soils at the present study site and thus, able to give an estimate of the depth to claypan. In this study, measured ECa was used as surrogate for the depth to claypan in the field.

Additional data included elevation data (vertical accuracy 3 to 5 cm) collected using global positioning system survey on 10 m transects (Fraisse et al., 2001; Kitchen et al., 2005). The data were processed into a DEM (Digital Elevation Model) from which slopes were calculated using ArcInfo® 9.2. Spatially distributed crop yields were measured from 1993 to 2002 using combines with commercially available yield sensing systems as explained in Kitchen et al. (2005). The data were processed to create productivity maps.

APEX Model Setup

APEX is a field/watershed scale model that provides flexibility to define weather, land use, soils, topography, and management practices such as tillage, crop rotations, and agricultural inputs. The model is a powerful tool to estimate the impact of different management scenarios on erosion, water quantity and quality, and soil quality, and simulates the routing processes for runoff, sediment, nutrients and herbicides/pesticides within and from the fields (Saleh et al., 2004; Wang et al., 2006). APEX performs all these processes across complex landscapes through the channel to small watersheds or field outlets **(**Srivastava et al., 2007; Gassman et al., 2010). The latest APEX version 0604 available when the study was initiated in December 2008 was used (Gassman et al., 2010).

The first step in APEX model set up was to divide the field into smaller spatial units called subareas represented with homogenous soil and topographic properties. A depth to claypan map was created using the clay depth estimated from measured ECa data, and intersected with the order 1 soil map of the field. Each resulting polygon with homogenous depth to claypan and soil type was treated as one subarea. Using this technique, the field was divided into 35 different subareas (Fig. 5.1). The DEM was used in ArcInfo for creating the flow paths in the field that were then used for describing the APEX routing scheme from one subarea to another and to the field outlet.

After subareas were delineated, soil and topographic characteristics were determined for each subarea based on field estimations and data collection. The profiles of the soils were adjusted based on the ECa measured depth to claypan data for each subarea; the range of claypan depth for each soil series is presented in Table 5.1. The routing channel dimensions were also measured in the field and were input to the model. The weather and management inputs were the same for the whole field. All the weather variables were collected from the weather station situated adjacent to the field from 1991 to 2002 and aggregated at daily time step.

The field was under uniform management since 1991 in a corn-soybean alternate annual crop rotation, where corn was planted during odd years and soybean during even years. The field was under mulch tillage maintaining around 30 percent residue cover with usually 1 disk and 1 or 2 field cultivation passes before the spring planting of the crop. There were exceptions: in 1995, corn was replaced with grain sorghum because of a delay in sowing as a consequence of a very wet spring, an extra fall tillage operation was also added to minimize the soil compaction caused by heavy rain (Lerch et al., 2005).

Once the model was set up, it was calibrated and validated for daily runoff, sediment, atrazine, dissolved nitrogen, and dissolved phosphorous loads. The calibration period was from 1993 to 1997, and the validation period was from 1998 to 2002. The model's goodness of fit was evaluated through the linear regression (r^2) method, Nash and Sutcliffe (1970) efficiency (NSE), and percent bias (Pbias). These criteria have been extensively used in modeling studies (Ramanarayanan et al., 1997; Santhi et al., 2001; Wang et al., 2007), and are explained in detail by Krause et al. (2005) and Moriasi et.al. (2007). Many researchers have considered various acceptable ranges for r^2, NSE, and Pbias based upon the amount of available measured data, output time interval, and purpose of the study. Moriasi et al. (2007) provided acceptable ranges for NSE and Pbias when quantifying the accuracy of monthly simulations of watershed runoff and pollutant loadings. Considering the daily time step, typically yielding less accurate simulations than a monthly time step, and the size of the drainage area, acceptable values in the present study for calibration and validation were defined as $r^2 > 0.5$ and NSE > 0.45. Acceptable values of Pbias were different depending on the model output: for runoff, the selected range was -25% < Pbias < 25%; and for sediment, atrazine load, and dissolved nitrogen and phosphorous loads, it was -55% < Pbias < 55%.

Index Development for CMA Delineation

Model output of crop yield, runoff, sediment, and atrazine were used for CMA delineation and indices were developed. The nitrogen and phosphorus outputs were not considered because of poor accuracy of the simulation results. The CMA designation in the field was based upon the 1993 to 2002 average annual value of the output variable, calculated for each subarea separately. A spatial distribution map for each output variable was developed using ArcInfo® (Fig. 5.3) and the total range of values for all the subareas was divided into six different classes using Jenks' optimization technique or natural break method in Arcinfo®. The Jenks optimization method is also known as the goodness of variance fit (GVF). It is used to minimize the squared deviations of the class means; optimization is achieved when the GVF is maximized (Jenks, 1967).

CMAs were estimated for each output separately and defined as the subareas that had amounts of output falling in the highest two classes, as divided by Jenks method. The three parameters: CD, surface Ksat, and SL in different combinations were estimated for all subareas and were correlated with each of the selected model output variables estimated for these subareas by estimating coefficients of correlation (r). The significance of r values was estimated by using t-statistics with n-2 degrees of freedom at 95% confidence level (Kaps and Lamberson, 2007). The n value was 35 as there were 35 different subareas delineated for the field and there were the same number of observations. When the correlation factor was significant, the combinations of these parameters were treated as a possible index to be used in future studies for CMA delineation. The combinations of parameters used for r value estimations with selected outputs were CD, surface Ksat, SL, CD/SL (CPI; Claypan Index), and (CD *Ksat)/SL (CCI; Conductivity Claypan Index).

The average crop yield from 1993 to 2002 for corn and soybean were also estimated for each subarea, in order to show any relationship between CMAs delineated for environmental hazards and crop productivity from these subareas. The similar statistical correlation procedure was used to estimate significant r values between measured and simulated crop yields and the developed indices.

Best Management Practices and Simulation Scenario Analyses

Four BMP scenarios were simulated in the field for a 30-year period (1979 to 2008; Table 5.2). Measured daily rainfall and temperature data were used for the whole simulation period but average solar radiation, relative humidity, and wind speed were simulated from 1979 to March, 1991 because measured data were not available. After March, 1991, all weather variables used in the model were measured.

BMP scenario 2 (Table 5.2) was divided into two parts based on the technique used to delineate the CMAs; in part a, CMAs were delineated using the model results while in part b, CMAs were delineated using the indices. In the model, CMAs were then managed with a summer (switch grass) and winter (rye) grass rotation, keeping the rest of the field with the same corn-soybean mulch till management. Switch grass was sown on 2nd of March every year and was harvested on July 7th. The rye grass was sown on 9th September and was harvested on March 1st of the following year; a pre-sowing nitrogen fertilizer was applied to both the grasses. The other 3 scenarios were not targeted to CMAs. They represent common current practices and were not targeted to any specific area. Scenario 3 is a mitigating practice, i.e., the loss of sediment and nutrients is captured by a filter strip located at the downstream edge of the drainage way. Scenarios 4 and 5 are two components of the current management of the field where corn is limited to the flatter south end of the field, the two areas on either side of the channel are in a wheat-soybean rotation, and the channel itself is planted with grass.

In scenario 3, a filter strip of area 1 ha was simulated immediately before the field outlet, i.e. subarea 35 (Fig. 5.1). Soil type for the filter strip was Argiaquaoll (Table 5.1) and was managed under fescue grass that was never harvested during the 30-year simulation period. In scenario 4, the total field was managed with a wheat-soybean rotation. Soybean production management was similar to that used during calibration and validation. Wheat operations included nitrogen and phosphorous application followed by mulch tillage prior to fall sowing and one more nitrogen application during the spring of the following year. Wheat was harvested in the summer of the following year.

Significant differences between model outputs from a BMP scenario and the baseline scenario (scenario 1) were evaluated using the non-parametric Wilcoxon statistical test (Kaps and Lamberson, 2007) using the SAS PROC NPAR1WAY procedure (SAS institute, 1999) at a confidence level of 95% ($P < 0.05$).

Results

Model Calibration and Validation

Calibration and validation results are presented in Figure 5.3. Runoff efficiency criteria for a daily time step were found to be strong, these ranged from r^2 from 0.69 to 0.74 and NSE from 0.68 to 0.72. In other APEX studies, efficiency criteria found by various researchers were in accordance with the present study, such as; Yin et al. (2008) in Huaihe River watershed, Henan province, China found r^2 and NSE values of 0.56 and 0.52 at a daily time step, Williams et al. (2006) had r^2 values of 0.72 and 0.73 in a Bison feedlot in North Dakota. The r^2 and NSE values in the simulation study done in claypan soils for 12 different plots (chapter 4) ranged from 0.52 to 0.98, and 0.46 to 0.94 respectively, and percent bias showed an over prediction and ranged between -12 to -59%. In contrast, present simulation of surface runoff had negligible bias (-0.8 and -2.2%; Fig. 5.3). The reason could be the longer calibration and validation periods and therefore higher number of runoff events in comparison to previous studies.

The APEX model was under predicting both nutrient (nitrogen and phosphorus) loads during the winter period, from December to February. The reason could be under prediction of surface runoff during the same period, as is indicated by a Pbias value of 21.6 % for average surface runoff during these three months over the whole simulation period. This would have caused a lower amount of nutrients transported to the field outlet by the model than was expected. This effect was not visible for atrazine losses because atrazine was only applied during late spring and no significant amount was left over on the soil surface for transport during the winter. For sediments, the APEX model considers snowmelt to have zero energy thus causing negligible erosion.

The sediment load was over predicted during the total simulation period, especially during validation. It was observed in the field that after a big runoff event there was always accumulation of sediment just before the field outlet, thus reducing the measured sediment yield in comparison to the actual sediment eroded and transported from the field. In contrast to sediment yield, atrazine load had strong efficiency criteria values and was slightly underestimated. Model APEX was able to simulate atrazine load effectively because the atrazine application rate and schedule was exactly known for the field during the whole simulation period. Also, including a tillage practice just after atrazine application effectively represented the incorporation of atrazine in the field.

All the model outputs were higher during the calibration period than during the validation period whether they were measured or simulated. It could be the higher precipitation during calibration (1993 to 1997; 1045 mm annual average) in comparison to the validation period (1998 to 2002; 990 mm annual average) there could be one more effect along with precipitation impact, i.e., the impact of changed management after 1991 when the field was taken over by the USDA-ARS Cropping System and Water Quality Research Unit. This change in field management may have caused gradual changes in soil properties that also tend to make calibration of the model more challenging, thus reducing the efficiency criteria values of model outputs during calibration and validation.

Runoff, atrazine load, and sediment yield had acceptable ranges of goodness of fit values at a daily time step level (Fig. 5.3) during calibration and validation. The two model outputs of nitrate-nitrogen and dissolved phosphorous did not have acceptable values for almost all of the efficiency criteria during either of the periods (Table 5.3).

Therefore nutrients estimated from the model were not used for CMA delineation and development of indices.

Index Development for CMA Delineation

APEX Model Based CMA Delineation: The average annual runoff, atrazine loads, and sediment yields were estimated for each subarea for 10 years from 1993 to 2002 as simulated by the model APEX. Threshold average annual values of model outputs used to delineate critical areas are shown in figure 5.4: runoff greater than 173 mm, atrazine loads greater than 32 g/ha, and sediment yields greater than 6.98 t/ha. All the resulting areas with runoff or loads greater than these values were treated as CMAs. The total critical management area delineated was 55 % (17.3 ha) of the total field area (32 ha) because of all the three model outputs. Thirty-four percent (10.8 ha) of total field area was found to be critical due to excess runoff generation, 33 % (10.2 ha) due to atrazine load, and 6 % (2.0 ha) due to sediment yield.

Only two subareas, subareas 31 and 32 (a total area of 2.0 ha), were found critical for both sediment yield and atrazine load. But one of these subareas (31; area of 0.8 ha) was not delineated as a runoff CMA. Almost 4 ha were found critical because of surface runoff and atrazine load together, whereas 5.7 ha field area was found to be critical only for atrazine load and 6.2 ha only for runoff (Fig. 5.4). Thus, in this field, areas generating higher amounts of surface runoff did not always generate higher amounts of atrazine and sediment, as determined by the APEX simulation results.

Two indices had significant correlation with model outputs: CPI (Claypan Index), and CCI (Conductivity Claypan Index). Coefficients of correlation (r) and scatter plots are shown in figure 5.5. As expected, these indices were negatively correlated with the three considered model outputs (runoff, sediment yield, and atrazine unit area load). The r value was considered significant if it was greater than 0.28 with 5% confidence interval estimated from a one tailed t-test. The CPI was significant but weakly correlated (r = -0.55) with two output variables (unit area atrazine load and sediment yield), but did not have significant correlation for surface runoff (-0.24). On the other hand, the correlation of CCI with runoff was significant and stronger (r = -0.77), but not with sediment yield, (r = -0.13). It was significant for atrazine load (r = -0.40) but weakly correlated. Therefore, it is necessary to consider both indices together to delineate CMAs that are generating higher amounts of surface runoff, sediment yield, and atrazine load. If only contaminants are relevant but not runoff, CPI would be the index of choice.

Indices for CMA Delineation: As model output was negatively correlated with these proposed indices, lower values of either index implied higher amounts of runof55f, atrazine or sediment generated from that subarea. After classifying subareas based on these index values and using Jenks optimization technique, subareas having values in the lowest two classes of indices were treated as CMAs (Fig. 5.6).

CMAs delineated by using the index based technique captured 80 % (13.8 ha) of CMAs delineated using model outputs (17.3 ha). Index based delineation captured 100 % of CMAs for runoff and sediment yield and 80 % for atrazine load (Fig. 5.7). Subareas 5 and 9, representing an area of 1 ha, were identified as CMAs by the index based technique but were not found critical based on model results. The subareas 14, 16, and 22 were delineated as CMAs by the model technique but not when using indices.

Average corn and soybean yields measured throughout the simulation period (1993 to 2002) were 5.8 and 2.3 t/ha, respectively, whereas area weighted average simulated corn and soybean yields for the same period were 4.6 and 1.2 t/ha, or 21% and 48% less, respectively. Both crop yields were under estimated by the model, possibly because of the poor simulation of plant nutrients by the model. However, the temporal variation in measured corn yield was similar to that of simulated corn yield. During the period 1993 to 2002, the year 1993, which was very wet had the highest measured and as well as simulated corn yield (7.2 t/ha for both measured and simulated). The smallest measured yields were obtained in 1994 and 1999, for soybean and corn yields respectively. The largest relative difference between measured and simulated yields occurred in 1994 (-56%) and 2002 (-62%) for corn and soybean respectively. The soybean crop did not have similar temporal variations for measured and simulated yields.

The spatial distribution of average measured and simulated crop yields for the total simulation period are shown in figure 5.8. While correlation between average annual measured and simulated corn yields across the 35 subareas was significant, it was weak (r = 0.36). There was no correlation between average measured and simulated soybean yields.

The estimated measured and simulated crop yields and the two indices for all of the subareas were used to calculate the coefficients of correlation (r) between indices and crop yields (Table 5.4). As expected, both indices were positively correlated with measured corn yields. However, measured soybean yields were not correlated with either one. The index CPI performed relatively well and had higher r values for measured as well as simulated yields. The r values between CPI and simulated and measured corn yields were 0.55 and 0.46, respectively, and were significant. These results show that CMAs delineated based on the CPI index, were also found to be low corn yielding areas.

The r value between CPI and simulated soybean yield was found to be significant but was insignificant for measured soybean yield, and the spatial correlation between measured and simulated soybean was also poor (Fig. 5.8) Therefore we cannot conclude that environmentally sensitive areas were also low soybean yielding areas. The soybean crop is also less susceptible to water stress in claypan regions (Thompson et al., 1991)

Best Management Practices and Simulation Scenario Analyses

The 30-year annual average runoff, sediment yield, and atrazine load were estimated for all the simulated scenarios. Only scenarios 2 and 3 were able to reduce significantly all the three model outputs in comparison to the control (Table 5.2). In scenario 2, when the model based delineated CMAs were targeted, there was a reduction of 26, 33, and 59% in runoff, sediment yield, and atrazine load respectively. When index based delineated CMAs were targeted, there was a reduction of 25, 32, and 55% in runoff, sediment yield, and atrazine load respectively. Total land area treated with the index based method was 44% of the field whereas it was 55% with the model based technique. Therefore the index based technique led to a lower amount of land taken out of cultivation for a significant amount of pollutant reduction than did the base scenario.

The most effective scenario was the establishment of a filter strip (Scenario # 3) just before the field outlet, which provided a reduction of 36, 79, and 35 percent for runoff, sediment yield, and atrazine load, respectively. The lower atrazine reduction obtained with scenario 2 can be explained by the lower net application of atrazine.

In scenario 4, the corn-soybean rotation was replaced by a soybean-wheat rotation; while there was no atrazine application and thus, no atrazine loss. This scenario led to small changes in sediment yield and runoff. Based on this information, if a BMP has to be applied to the field, it should be a filter strip at the outlet or a change in cropping systems in favor of grasses targeted to CMAs delineated by the CPI and CCI indices developed for claypan soils.

Discussion

CMA Delineation

The APEX model has been extensively used to estimate the effects of agricultural, forest lands, and dairy and meat farming on runoff, sediment yield, herbicides and nutrients loads (Saleh et al., 2004; Williams et al., 2006; Wang et al., 2007; Wang et al., 2008; Yin et al., 2008; Gassman et al., 2009). In many of the studies, different BMPs were analyzed for their potential to reduce transport of these pollutants to the streams at subarea or watershed levels (Qui et al., 2002; Paudel et al., 2003; Harman et al., 2004; Wills, 2008). However, the APEX model has never been used for delineating CMAs at a subarea scale.

The study presented in chapter 4 used the APEX model for simulating outputs from 12 plots in claypan soils after sub-dividing each plot into different landscape units. APEX was able to successfully distinguish the landscape positions and to predict areas that were more critical in generating surface runoff and atrazine loads. This finding was utilized to delineate CMAs based on APEX performance at a subarea scale.

The CMAs delineated by the model were mainly at backslope landscape positions of the field, where the slope is steepest and the top soil depth is most shallow. These subareas generated excessive runoff as a result of the lower permeability of the surface layer and the smaller water holding capacity caused by a shallow depth to claypan. These findings confirm our plot scale results presented in chapter 4. In contrast, these areas were not always high sediment generating areas, as predicted by APEX. Out of seven different equations for soil loss estimation in the APEX model, a theoretically developed equation MUST (Modified Universal Soil Loss Equation Theoretically developed; Williams et al. 2006) was found to have the best results in the field. This equation considers six different factors for soil loss estimation. Four of the factors were similar for the whole field, i.e., runoff factor based on amount of runoff volume and peak flow (X), crop management factor (CVF), erosion control factor (PE), and the coarse fragment factor (ROKF). The two other factors slope and slope length (SL), and soil erodibility factor (EK), were different among the subareas and were the reasons for sediment loss variation between subareas. The EK is dependent upon soil texture and soil organic matter; its variability is based on soil series as shown in Table 5.1. If the soil texture has higher clay content in the surface soil, a lower value is used for EK and a lower soil loss would occur. Surface runoff generation is independent of these factors (Steglich and Williams, 2008).

One would expect that atrazine loss would be dependent on runoff generation. However, the relationship was not as strong as we had thought. The total CMAs delineated for excess atrazine losses represented only 38 % of the CMAs delineated by excess runoff. Runoff generation from any subarea was found to be highly dependent on the surface Ksat, while depth to claypan and slope were more important for atrazine loss. Organic carbon could have played an important role in atrazine adsorption and/or transport and was variable among the subareas (Table 5.1); runoff was not directly related to organic carbon (Steglich and Williams, 2008). This could explain the poor matching of CMAs delineated for both of these outputs.

The results of this simulation study and other studies done in similar soils (Kitchen et al., 2005; Lerch et al., 2005; Fraisse et al., 2001) confirm that the claypan depth is an important parameter impacting not only the generation of non point source pollutants and runoff but also the crop yield. In the present study, the coefficients of correlation (r) between claypan depth and runoff, sediment yield, and atrazine load generated were -0.39, -0.55, and -0.44, respectively. Sediment yield and atrazine load were most impacted by claypan depth. After including the slope factor with the depth to claypan, thus creating the claypan index (CPI), the r value was increased substantially for atrazine load to -0.55, and was left unchanged for sediment yield to -0.55. CPI was able to delineate CMAs that generated the highest sediment yield and atrazine load. The r value between Ksat and runoff was -0.82, therefore, Ksat was also included with the CPI index and a new index was developed called the conductivity claypan index (CCI, equation 3). The r value between CCI and runoff was now found to be -0.77. CMAs delineated with these two indices were able to capture 80% of CMAs delineated by the model outputs as the indices had a significant correlation with the simulated outputs runoff, sediment yield, and atrazine load.

The positive correlation was expected between index and crop yield because lower values of these indices, caused by a high slope, a low depth to claypan, or a low surface hydraulic conductivity, are indicative of more sensitive areas that are likely to produce less. Soybean yield was not well represented spatially by these indices; because there was lower variability in measured soybean yield in the field as estimated by Kitchen et al (2005). This lower variability could be attributed to reduced water demand of soybean compared to corn (Thompson et al., 1991). Kitchen et al. (2005) developed the productivity zones in the same field, based on slope and ECa data. They found satisfactory agreement between measured corn and soybean yields and yield zones delineated using ECa and slope data. They also reported that crop yields on the field were still impacted by historical management from 1930 to 1980. During that period, part of the field was managed in a different direction, which caused abrupt variations in the field soil properties. These differences were detected in measured crop yields. Whereas these variations were not represented in the model as all of the properties were averaged across the subareas. Similarly, averaging crop yields within each subarea tends to decrease the spatial variability in the subareas. These two averaging procedures had increased the uncertainty in the model outputs and could explain the weak correlation (r values of 0.46 and 0.55) between measured and simulated corn yields and the CPI index.

Simulation Scenario Analyses

In scenario 4, replacing the corn-soybean rotation with a soybean-wheat rotation was expected to reduce runoff, sediment yield, and atrazine load in two ways: elimination of atrazine load because there would be no application of atrazine, and reduction of runoff and sediment loss because wheat has a longer growing period in comparison to corn and provides ground cover during the winter. However, simulation results suggested there was no significant change in sediment yield (-1%) or in surface runoff (4%) in comparison to the control.

Establishment of a filter strip just before the field outlet was able to reduce runoff, sediment yield, and atrazine loads significantly in comparison to the control. The impact of filter strips in reducing runoff and non-point source pollutants is well documented in the literature (Gilliam, 1994; Udawatta et al., 2002; Lovell and Sullivan, 2006; Kumar et al., 2008). Lin et al. (2008) did a lysimeter study in Missouri to ascertain the impact of filter strips in reducing atrazine by degrading it to lower toxicity metabolites; they found that switch grass converted 80% of atrazine into less toxic metabolites and 47% less mobile byproducts. Therefore filter strips do not only reduce the mobility but also the toxicity of pollutants.

In comparison to scenario 3 (establishment of filter strip), scenario 2 (targeting CMAs) would have extended benefits in land reclamation. It has been found that agricultural land taken out of cultivation and put under grasses would improve soil quality significantly (Jiang et al., 2008). Udawatta et al. (2008) found significant differences in soil hydraulic properties of land under row crop cultivation and CRP (Conservation Resource Program), in claypan soils. Soils under CRP had better pore structure, higher saturated hydraulic conductivity, and lower bulk density.

Summary and Conclusions

The present study was conducted to delineate Critical Management Areas (CMAs) in a 32-ha field located in the Goodwater Creek Experimental Watershed, with predominant soils classified as claypan soils (fine, smectitic, mesic, Aeric Vertic Epiaqualfs and Vertic Albaqualfs). The CMAs delineated were generating higher amounts of runoff, sediment yield, and atrazine load and tended to produce lower yields for corn.

The field was divided into 35 subareas based on topography, depth to claypan, and soil type. The APEX model was calibrated and validated for runoff, sediment yield, and atrazine load at the field outlet, from 1993 to 2002. The model was able to simulate these parameters within acceptable limits. The average annual runoff, sediment yield, atrazine load, and corn and soybean yields were estimated for all 35 subareas during the total simulation period. Based on Jenks optimization technique, all the outputs were divided into five different classes and the subareas that produced the highest amounts of runoff, sediment yield, and atrazine load were considered as CMAs. The total critical management areas delineated were 55 % (17.3 ha) of the total field area (32 ha) due to all three model outputs. Thirty-four percent (10.8 ha) of the total field area was found to be critical because of excess runoff generation, 33 % (10.2 ha) due to atrazine load, and 6 % (2.0 ha) due to sediment yield.

Two indices, the CPI (Claypan Index); calculated by dividing the Clay Depth by the average Slope, and the CCI (Conductivity Claypan Index), calculated by multiplying CPI by the surface saturated hydraulic conductivity, were estimated for all the subareas. Significant correlations were found between the APEX model estimated runoff, sediment yield, atrazine load, and corn yield and these indices. Therefore these parameters were also used to estimate CMAs in the field.

Index based delineation of CMAs captured 80% of the CMAs delineated by the model simulation technique. We conclude that further investigation are warranted to determine whether these two indices, CPI and CCI, can be used for delineating CMAs in claypan areas without the use of complex hydrologic models. The soil and topography data used to calculate these indices are accessible and can be used to delineate critical areas for targeting BMPs in claypan areas. The scope of the present study was limited to a field scale study using finer scale elevation and soil data. Behavior of indices developed using coarser scale data from the USDA-Natural Resources Conservation Service (USDA-NRCS) Soil Survey Geographic soil database (SSURGO; 1:24000 scale) soil data and USGS DEM is presently undetermined. If these indices can delineate CMAs using the coarser scale data, they could be used to delineate CMAs at a watershed scale in claypan regions.

The CMAs delineated within the field were also found to be low corn yield producing areas. Environmentally sensitive areas in claypan soils were also found to be low yielding areas; therefore land reclamation programs including CRP would be more beneficial in these regions because if these areas had to be taken out of agriculture for other management to reduce detrimental impact on downstream water quality, there would not be considerable reduction in average crop yields.

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Tables

Table 5. 1: Measured soil properties as input in the model, after minor adjustments.

Soil Series	Surface Soil Properties							Claypan Depth Range (cm)
	Organic C (%)	pH	Cation Exchange Capacity (CEC; c mol/g)	Ksat (mm/h)	BD	Texture (%)		
						Silt	Clay	
Adco	1.1	5.8	21.7	47.7	1.4	72.4	21.9	15 - 38
Argialboll	1.2	5.7	19.8	136.3	1.4	71.0	23.8	30 - 55
Argiaquolls	1.2	5.0	18.5	12.5	1.3	79.3	20.2	60 - 100
Leonard	1.0	5.8	17.1	3.4	1.5	70.1	18.7	25 - 53
Mexico	0.9	5.6	19.4	5.6	1.4	78.3	16.2	15 - 40
Putnam	1.3	5.0	20.1	153.1	1.4	70.4	23.2	30

$ In order 1 soil survey Leonard was divided into two different series, whereas in the model it was termed as one soil type.
* Only one value of clay depth was used.

Table 5. 2: Scenarios with Best Management Practices (BMP) applied, and 30 year (1979 to 2008) simulation results of annual average runoff, sediment yield, and atrazine load.

Scenario	Best Management Practices	Runoff		Sediment Yield		Atrazine Load	
		mm	Percent Change	t/ha	Percent Change	Kg/ha	Percent Change
1	Control: no BMPs applied and existing crop management in the field was simulated	242	-	7.5	-	14.5	-
2	All the CMAs were cropped with summer (switch grass) and winter grass (rye grass) rotation, rest of the field was left under existing crop management. Based on the CMAs targeted this scenario was further divided into two parts:						
(a)	CMAs Delineated by model based technique	178*	-26	5.0*	-33	5.9*	-59
(b)	CMAs delineated by Indices based technique	181*	-25	5.1*	-32	6.5*	-55
3	1 ha area immediately before the field outlet was managed as filter strip, rest of the field with existing crop management	154*	-36	1.6*	-79	9.4*	-35
4	The Field was put under wheat-soybean crop rotation	253	4	6.4	-14	NA	NA
5	Subareas with main channel of the field were put under summer and winter grass rotation, rest of the field was left under existing crop management	243	0	7.4	-1	13.2	-9

* Values significantly different than control

Table 5. 3: Calibration and validation goodness of fit efficiency values for daily dissolved nitrogen and phosphorus.

Model Output	Calibration (1993 to 1997)			Validation (1998 to 2002)		
	r^2	NSE	Pbias (%)	r^2	NSE	Pbias (%)
Nitrate- Nitrogen	0.31	0.18	58.1	0.17	0.16	46.1
Dissolved Phosphorus	0.55*	0.22	71.5	0.14	-0.05	78.9

* Value in acceptable range.

Table 5. 4: Coefficients of correlation (r) between measured and simulated crop yields and indices for the 35 subareas.

Crop	R value with Index CPI (Claypan Index)	R Value with Index CCI (Conductivity Claypan Index)
Measured		
Corn	0.46	0.41
Soybean	0.16	-0.16
Simulated		
Corn	0.55	0.16
Soybean	0.65	0.39

Figures

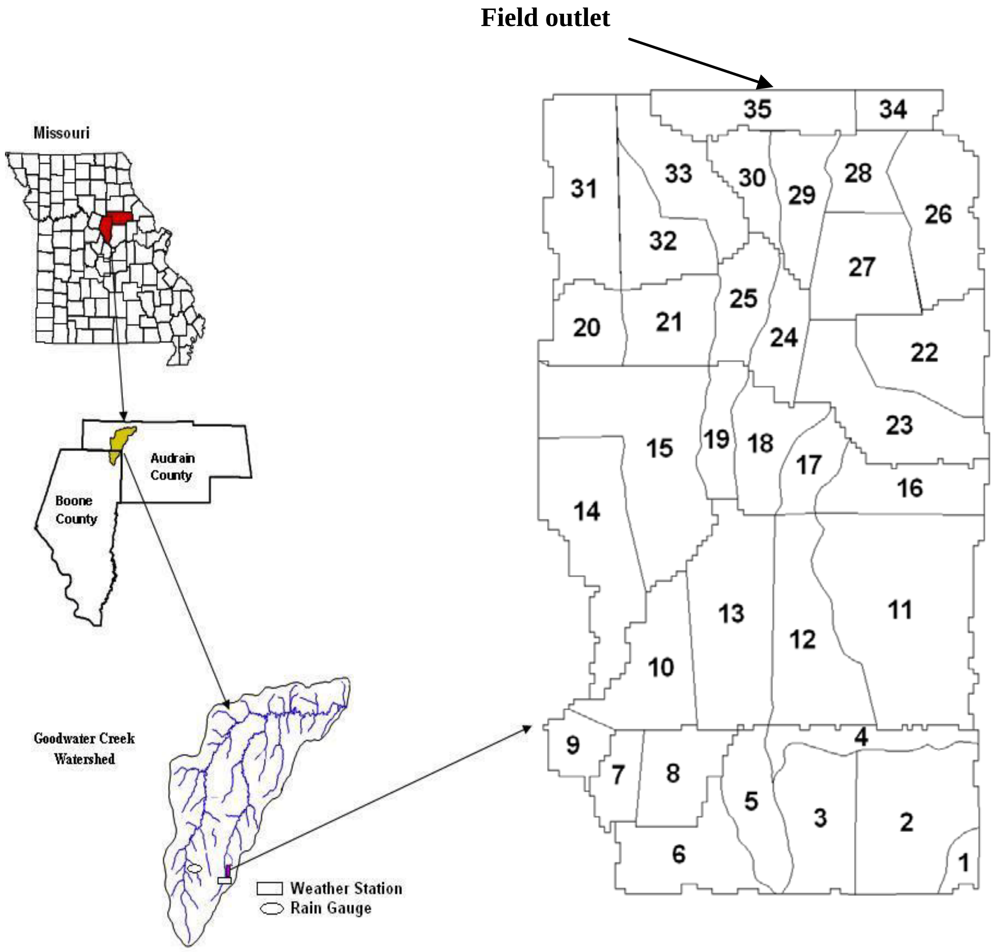


Figure 5. 1: Location of study site (39° 13' 48"N, 92° 7' 12" W), and Study Field divided into 35 different subareas with each subarea having homogenous depth to claypan, and soil type.

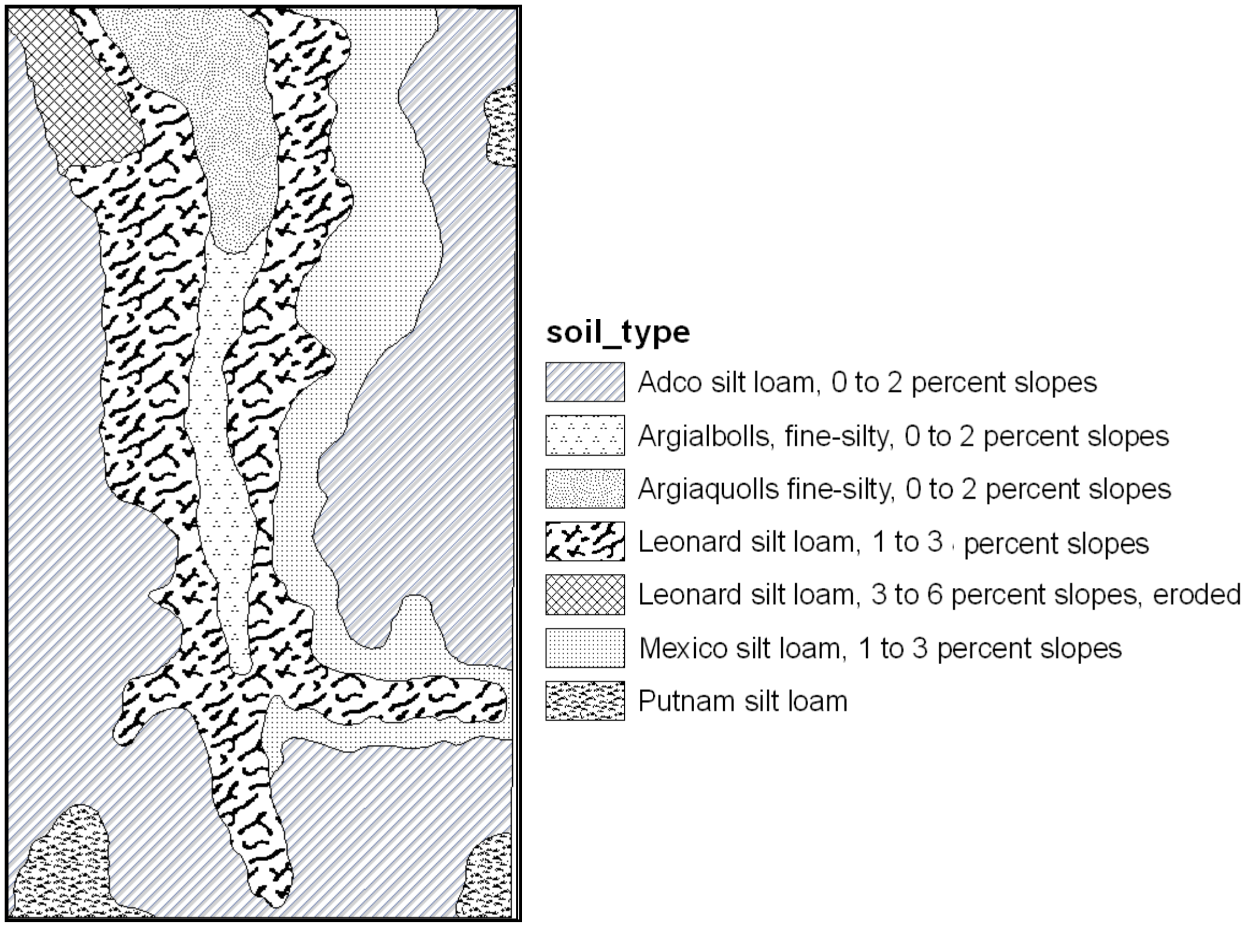


Figure 5. 2: Soil classification of the field based on order 1 soil survey (1:5,000 scale).

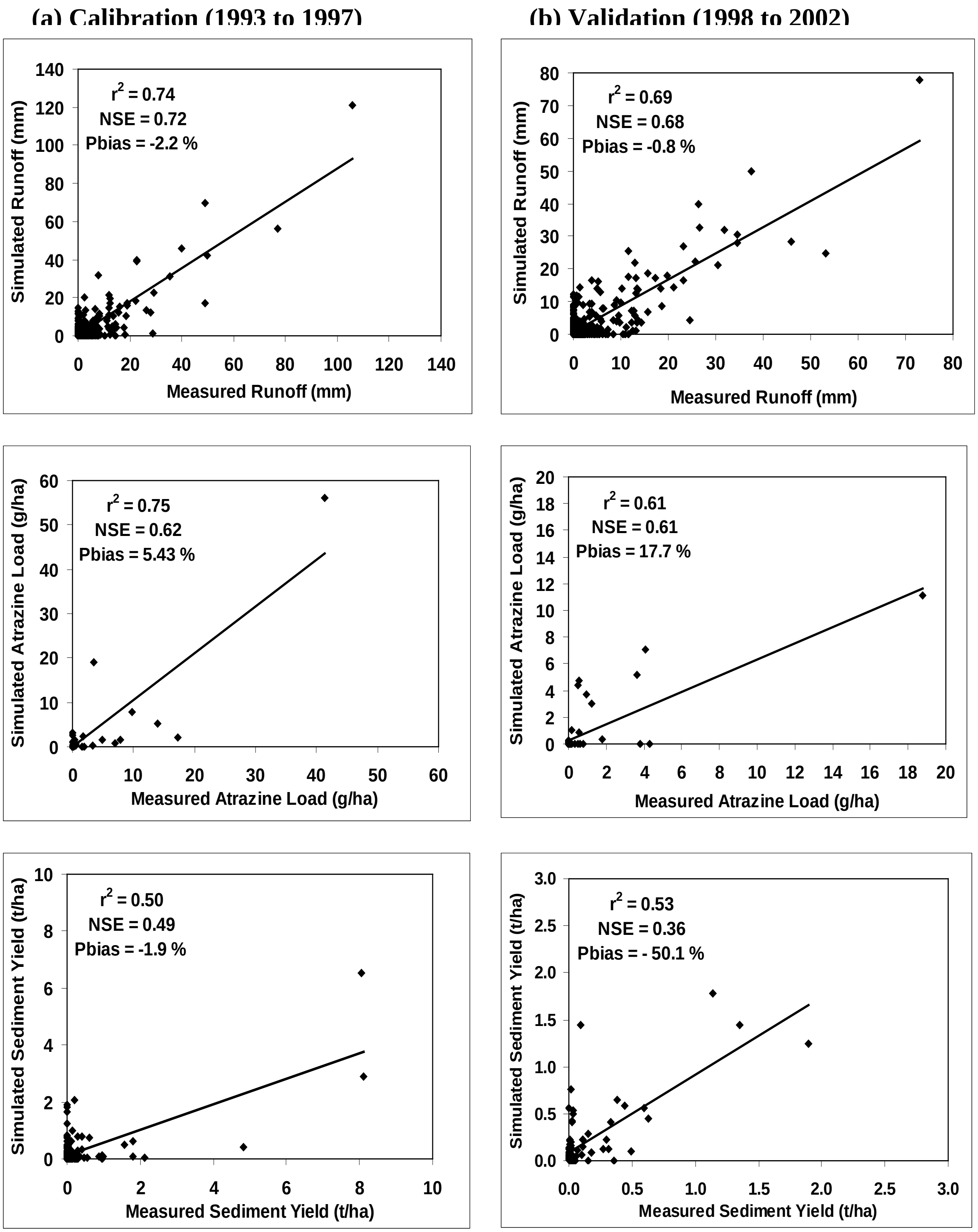
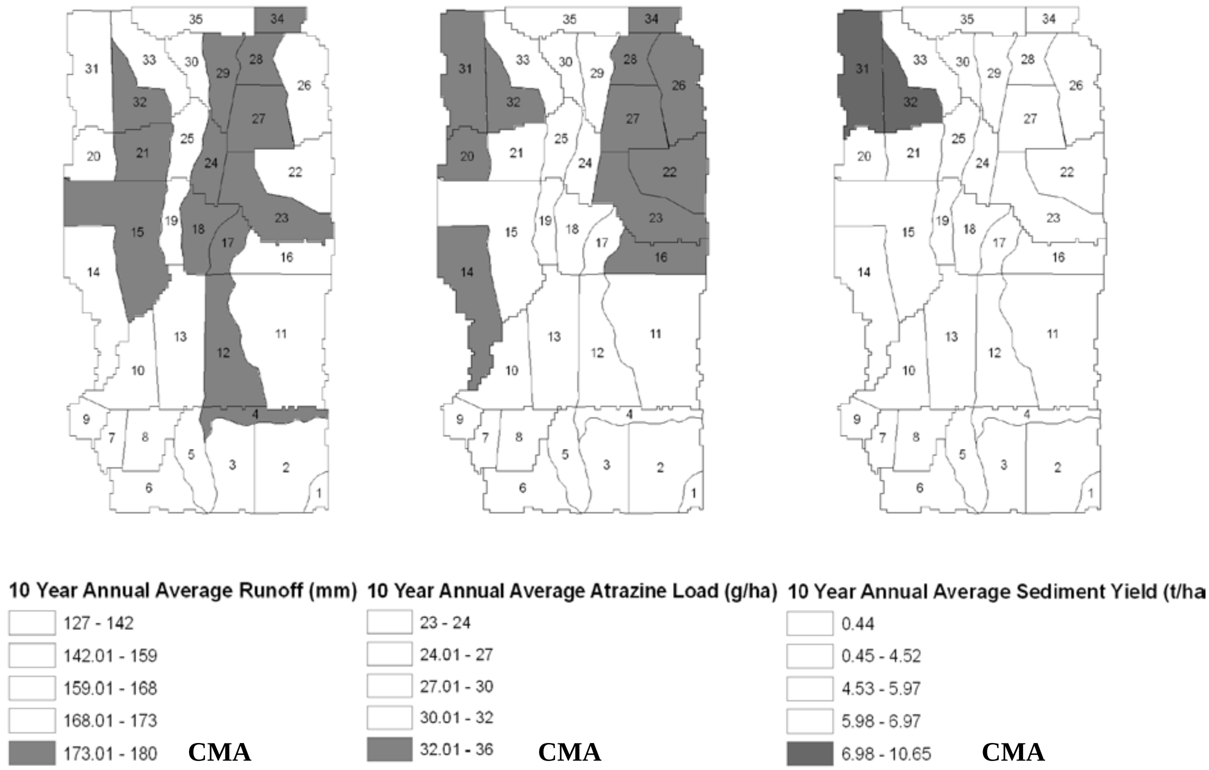
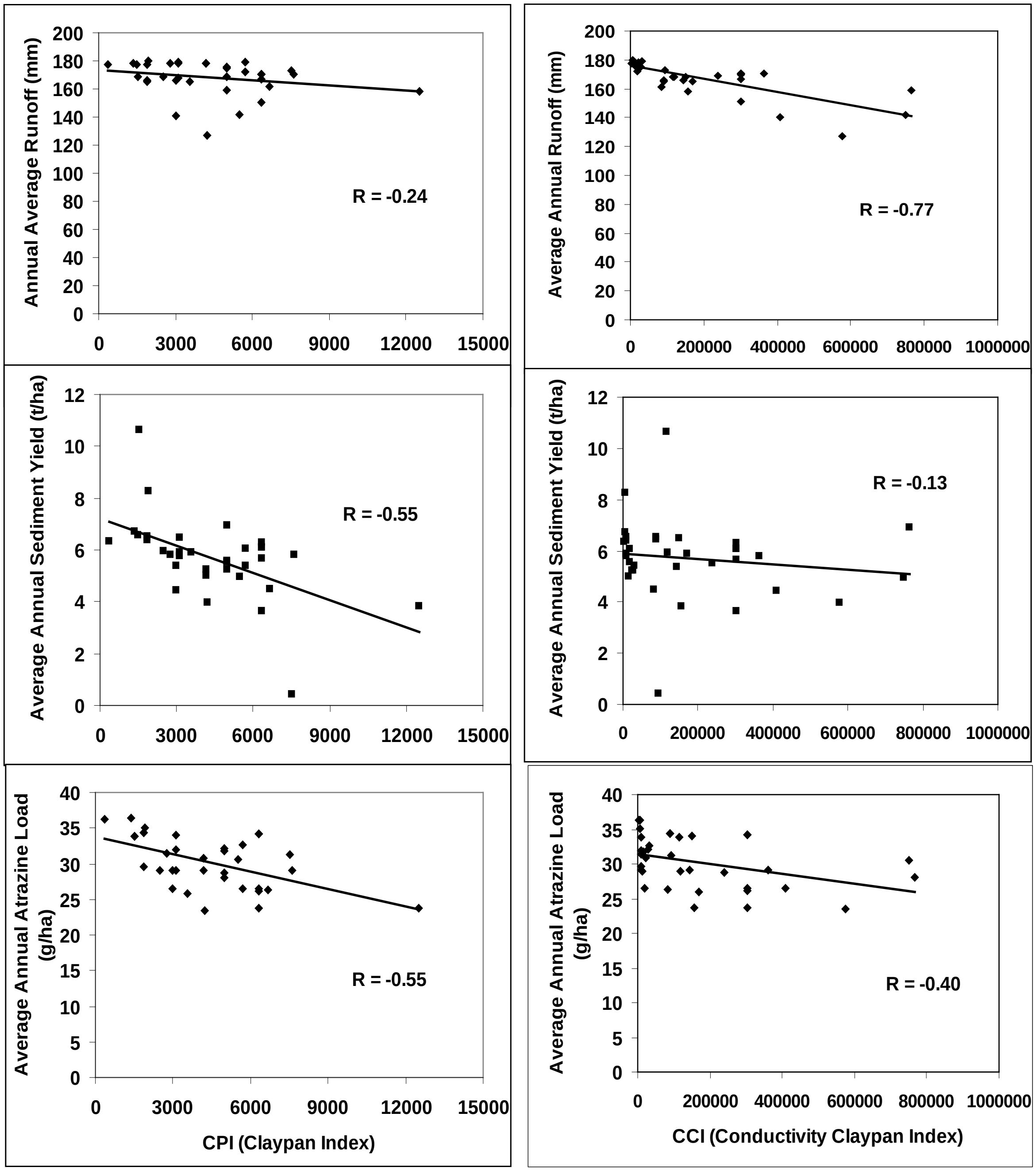


Figure 5. 3: Daily output simulated and measured graphs for the Field. (a) Calibration graphs for daily runoff (mm), atrazine load (g/ha), and sediment yield (t/ha), and (b) Validation graphs for daily runoff (mm), atrazine load (g/ha), and sediment yield (t/ha).



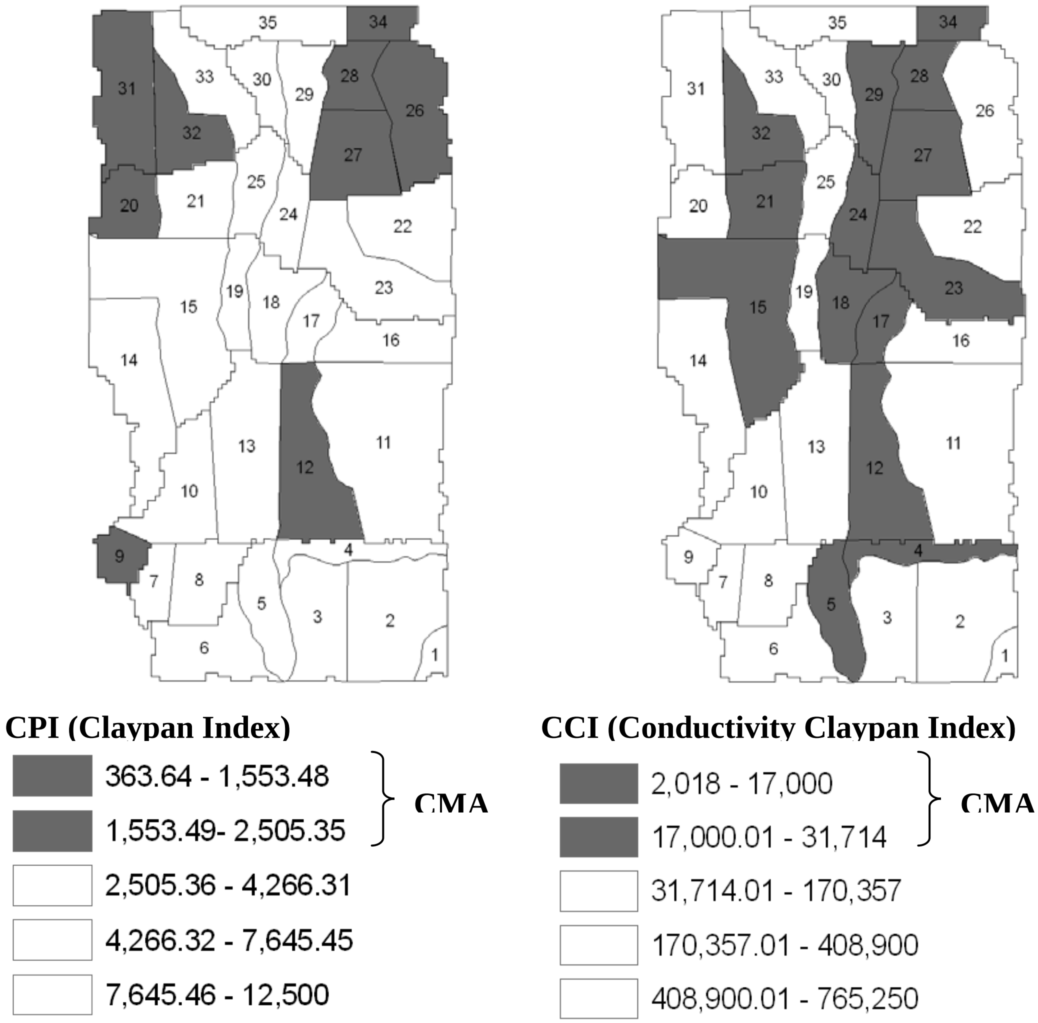
(a) (b) (c)

Figure 5. 4: CMAs (Critical Management Area) delineated for study field using APEX model outputs for 10 years (1993 to 2002) average annual for (a) runoff, (b) atrazine load, and (c) sediment yield.



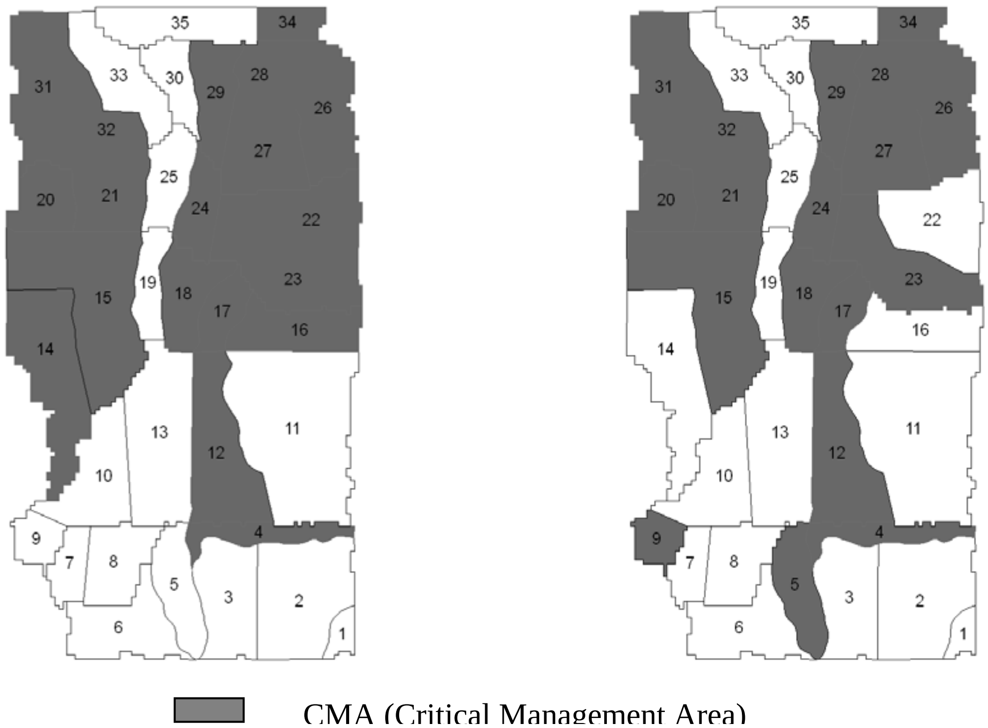
(a) (b)

Figure 5. 5: Scatter plots and coefficients of correlation (r) between model outputs and indices; (a) between average annual runoff, sediment yield, and atrazine load and CPI = CD/SL, (b) between average annual runoff, sediment yield, and atrazine load and CCI = CD *Ksat/SL, where, CD = depth to claypan, Ksat = saturated hydraulic conductivity of the surface soil layer, and SL = average slope.



(a) (b)

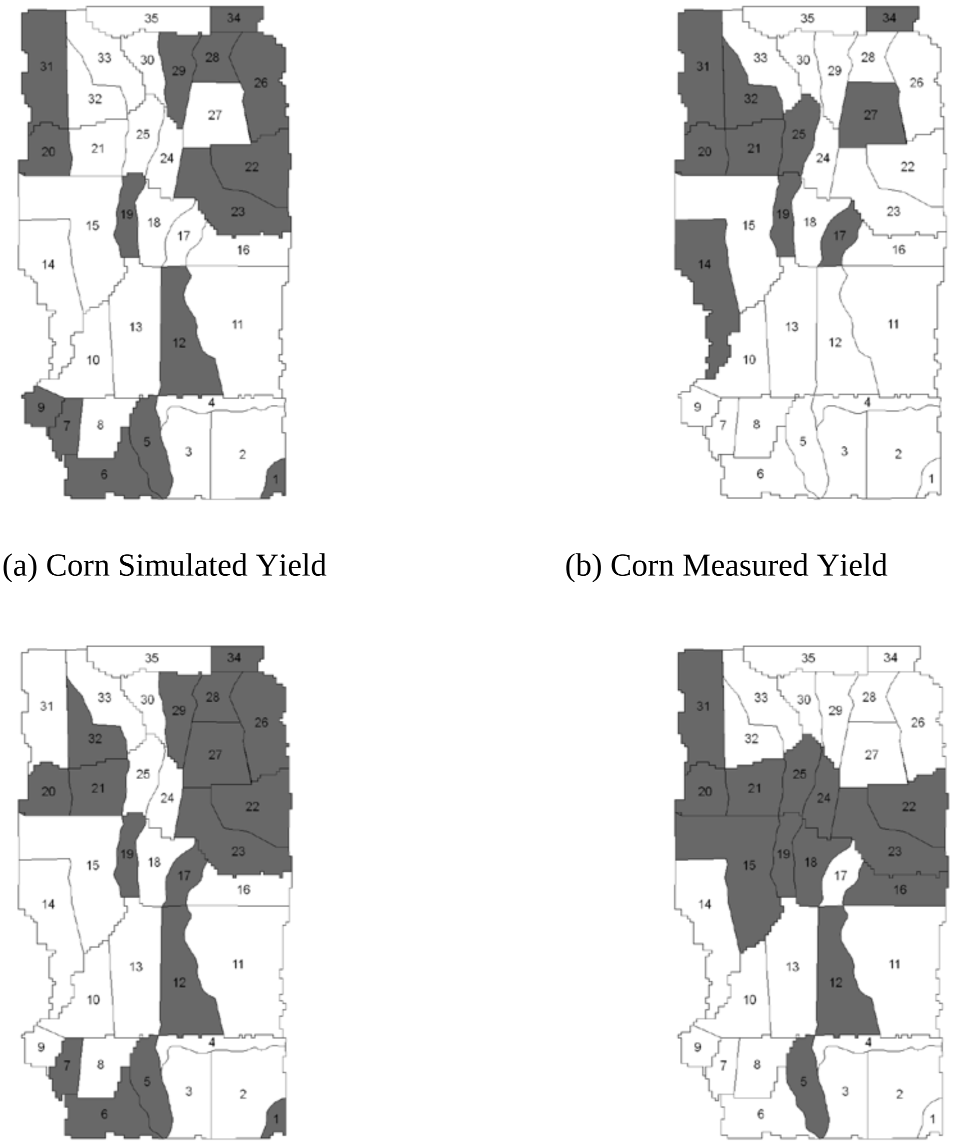
Figure 5. 6: CMAs (Critical Management Area) delineated using two indices (a) CPI, and (b) CCI in the field.



(a) Total CMAs delineated by model outputs

(b) Total CMAs delineated by indices CPI and CCI

Figure 5. 7: CMAs (Critical Management Area) delineated using: (a) APEX model outputs, and (b) using two indices CPI (Claypan Index) and CCI (Conductivity Claypan Index).



(a) Corn Simulated Yield (b) Corn Measured Yield

(c) Soybean Simulated Yield (d) Soybean Measured Yield

Figure 5. 8: Spatial distribution of measured and simulated annual average crop yield during total simulation period (1993 to 2002), the shaded regions in all the maps were the lowest two classes of crop yields as classified into total of five classes by the Jenks optimization technique.

CHAPTER 6

ASSESSING THE IMPACT OF LONG-TERM CULTIVATION ON RUNOFF, SEDIMENT YIELD, ATRAZINE LOAD, AND CROP YIELD FROM CLAYPAN SOILS USING THE SIMULATION MODEL APEX

Abstract

Intensive agriculture during the last century had detrimental impacts on soil and water quality and is noticeable by means of increased runoff and associated non-point source pollutant losses. This simulation study estimated the impact of long-term agriculture on surface runoff, sediment yield, atrazine load, and corn and soybeans yields. A calibrated and validated APEX (Agricultural Policy Environmental eXtender) model for a 32 ha field was used to simulate the impact of long-term agriculture on selected model outputs. Soil samples were collected from two fields with claypan soils, one that has been under cultivation for more than 100 years (Field 1) and a native prairie (Tucker Prairie; TP) that has never been tilled. Measured soil properties were considered to represent post- and pre-agricultural scenarios. A previous model to estimate soil loss and/or deposition areas using remote sensing and historical pictures of field 1, elevation, and slope (R^2 = 0.66) was applied on Field 1 to create a soil loss and deposition map of the field. From that, two soil profiles were defined: the 'current profile' of Field 1 and the other 'enhanced profile' before the cultivation was started. Using two different sets of soil properties and profiles, four scenarios were established: 1. Current profile and Field 1 soil properties (base line; CPF1), 2. Enhanced profile and Field 1 soil properties (EPF1), 3. Current soil profile and TP soil properties (CPTP), and 4. Enhanced soil profile and TP

soil properties (EPTP). The APEX model was run for thirty years (1978 to 2007) for the four scenarios with a corn-soybean crop rotation and a mulch tillage management. The selected model outputs were compared at an annual time scale to analyze the impact of long-term agriculture. There was a significant increase in annual average atrazine load (82%), and a reduction in corn (39%) and soybean (75%) yields after the field was under cultivation for more than 100 years. Atrazine load and crop yields were more sensitive to the soil properties, whereas runoff and sediment yield were more dependent on the current vegetation in the field. These results show that the restoration of agricultural lands would be beneficial not only to enhance crop yields but also to reduce non-point source pollutants.

Introduction

Conservation of fertile soil is of prime importance not only for economical reasons but also to maintain soil quality (McCracken 1987). Accelerated erosion can cause major on-site and offsite agronomic, environmental, engineering, or aesthetic problems, as well as cultural disturbances. Accelerated erosion was identified as the cause of downfall for many ancient civilizations (Olson 1981), such as Harappa in western India (Lal 1998) or the Mayan civilization in Central America (Olson 1985). This danger is still lingering in our present society.

Long-term cultivation impacts the soils because of agricultural traffic, tillage, and bare soil in between crop rotations (Fuentes et al. 2004). All factors tend to increase erosion from the soil surface. A major impact of erosion is often the removal of a coarser textured topsoil, organic carbon, and associated nitrogen (N) and phosphorous (P), and exposure of a finer textured-subsoil that often has higher bulk density and lower hydraulic conductivity (Lal 1997; Jagadamma et al. 2009). Bowman et al. (1990) compared rangeland soils from four analogous sites that were under cultivation for 0, 3, 20, and 60 years and found that soils with 60 years of cultivation had 55 to 63% reduction in total soil organic N, C, and P in the first 15 cm soil layer. Seobi et al. (2005) found that soils under row crop had higher bulk density and lower porosity than soils under perennial grass and tree buffers. They also concluded that, after six years of establishing the buffers, soil under buffers were improved, could store more water and hence had lower runoff and less sediment, nutrient, and herbicide losses. Similarly, Rachman et al. (2004) showed that areas under row crop cultivation had higher bulk density and clay content and lower porosity and saturated hydraulic conductivity than areas under perennial grass hedges for more than ten years, for the same soil.

Many ongoing conservation efforts in the United States attempt to address soil loss threats. Conservation tillage and crop rotations were able to reduce soil erosion by 40% between 1982 and 1997 (Claassen et al. 2004). Programs like land retirement and putting row crop fields under permanent cover have reduced soil erosion and improved water and soil quality, wildlife habitat, and enhanced carbon sequestration (Lambert et al. 2007; Feather et al. 1999; Ribaudo et al. 1990). Around 160 structural and management farming practices are listed in the USDA-NRCS (United States Department of Agriculture, Natural Resources Conservation Service); the cost of implementation of many of them are being shared between local or federal governments and the farmers (Lambert et al. 2007). Billions of dollars are being utilized in these programs, and each one of the practices listed is intended to improve one of the principal concerns in USDA conservation policy (Khanna et al. 2002).

One such conservation practice is the land retirement program that was planned to restore soil health to an extent that the adverse effects of long-term cultivation could be reversed as much as possible. The Conservation Resource Program (CRP) targets the environmentally sensitive areas to take them out of production and put them under permanent grass cover for 10 to 15 years. Many studies found significant improvements in soil physical and chemical properties between land under CRP and continuous cultivation (Gebhart 1994; Schwartz et al. 2003; Jiang et al. 2007; Udawatta et al. 2008). Wu et al. (1997) estimated the erodibility index (EI) of the soils under CRP and cropland using remote sensing and GIS (Geographical Information System) in Finney County, Kansas. They found that soils under CRP had lower EI and were more fertile than soils under continuous cultivation. These programs are showing favorable results with respect to soil quality. The one objective of implementing the conservation practices has still to be verified, i.e. the impact of improved soil quality on crop yield, runoff, sediment yield, and agri-chemical losses, once they would be brought back to cultivation.

The adverse impact of soil erosion on the environment and crop yield is more pronounced if the underlying soils have higher clay content (Lal 1997). Therefore the problem of soil erosion because of long-term cultivation in the claypan soils of mid-western US is even more severe. Kitchen et al. (2005) found that areas with shallow claypan had low corn and soybean yields. Other studies have shown that, in shallow claypan soils, surface losses of herbicides and nutrients with runoff were higher (Ghidey et al. 1997; Ghidey and Alberts 1999; Lerch et al. 2005). Chapters 4 and 5 of the present dissertation are in agreement with these findings. Since conservation practices have been going on in the claypan area of Missouri, there was around 4% of crop land in the state of

Missouri that was under CRP by 1997 (USDA NRCS, 2004). A survey study in Texas High Plains by Johnson et al. (1997) suggested that 69% of farmers would start cropping the land currently under CRP once their contract would finish, and 86% of farmers responded their decision of bringing back CRP acres into cropland would be dependent upon the financial value of commodities. Therefore, if this survey is indicative of post CRP land use, it probably implies most of the current acres under CRP would again be used in crop production. The improvement in soil properties after CRP should minimize the negative impacts of agriculture by reducing the amount of runoff and non-point source pollutants at the field outlet and should also enhance the land productivity

Two land cover scenarios that produce extreme variations in soil quality are land under continuous cultivation for more than 100 years and the native prairie. Udawatta et al. (2008) found significant differences in pore size distribution of soils under row crop cultivation and a native prairie that had never been tilled. Fuentes et al. (2004) also found significant differences in saturated hydraulic conductivity and soil water retention between soils that had never been tilled and agricultural land. In addition to changes in soil properties, extensive agricultural practices over the last 100 years also reduce the topsoil depth. As shown in chapter 3 of the present dissertation, the field under cultivation for more than 100 years had lost almost 20 to 30 cm of topsoil in comparison to the native prairie site that had never been tilled.

Based on the above discussion, this simulation study was designed to evaluate the impact of these two extreme soil property and soil profile scenarios on crop yield, runoff, sediment yield, and atrazine loads. Assessing these scenarios in field conditions would require long temporal data collection; therefore a simulation study is practically the only available technique.

In this study, the Agricultural Policy/Environmental eXtender (APEX; Williams et al., 2008) was used to simulate runoff, sediment yield, atrazine loss, and crop yield from a 32 ha field in claypan soils, with two soil profile scenarios: one for a native prairie and the other for a field that has been cultivated for more than 100 years. APEX is a field/watershed scale model that provides flexibility to define weather, landuse, soils, topography, and management practices such as tillage, crop rotation, and agriculture inputs. The model can also take into account the impact of different configurations of management on erosion, water quantity and quality, soil quality, while allowing for routing processes for runoff, sediments, nutrients and herbicides/pesticides within and from fields (Saleh et al., 2004; Wang et al., 2006). In many studies for different environments with various agricultural management practices, APEX has been successfully used to simulate runoff, herbicides and nutrients, and crop yields inside and at the outlet of watersheds (Saleh et al., 2004; Williams et al., 2006; Wang et al., 2007; Gassman et al., 2010).

The hypothesis for the present study was native prairie soils would produce better crop yields and reduced runoff, sediment yield, and atrazine loads in comparison to soils under continuous cultivation since the last 100 years. The objective of present study was to estimate the variation in thirty years of simulated runoff, sediment yield, atrazine load, and crop yield on a field when it has never been tilled before, and after it has been tilled over 100 years.

Methodology

Study Area and Cropping System

The present simulation study was done on a 32 ha field (Field 1) located in the central part of Missouri (Figure 6.1). The field was characterized by claypan soils (fine, smectitic, mesic, Aeric Vertic Epiaqualfs and Vertic Albaqualfs); these soils include an argillic horizon, which varies in depth across Field 1. The summit had a moderate depth to claypan (35 cm), the backslope positions had the shallowest depth to claypan (10 cm), and the depositional zone at the toeslope or footslope position of the landscape had the deepest clay depths (50 to 100 cm; Myers et al. 2007). This argillic horizon had almost double the clay content of the surface soil layer, and had a very low hydraulic conductivity (0.01 mm/hr; Chapter 3). These properties tend to induce higher runoff and to generate higher losses of agri-chemicals (Chapters 4 and 5, this dissertation; Ghidey et al; 1997, Ghidey and Alberts, 1999, Lerch et al. 2005; Jiang et al. 2007). Furthermore because of the high clay content of the argillic horizon, these soils restrict root penetration to deeper soil layers, which can impact crop yield especially in landscapes with shallow claypans (Myers et al. 2007).

The historical management records for the Field 1 site were presented by Lerch et al. (2005). They report that during the first half of the 20th century, the most likely crops were corn and wheat (*Triticum aestivum*) under plow and disk tillage. During the later part of the century, plowing and disk tillage were continued but the cropping system changed to corn, soybean and grain sorghum (*Sorghum bicolor*). After 1991, the field was under uniform management with a corn/soybean rotation with mulch tillage, and has been managed by the USDA-ARS Cropping Systems and Water Quality Research Unit (CSWQRU) in Columbia, MO.

Another field, a native prairie (Tucker Prairie; TP) representative of soils that have never been tilled, was used for measurement of soil properties. TP is also located in central Missouri and is under native vegetation (Figure 6.1; Dahlman and Kucera, 1965). Soils at the TP site are also classified as claypan soils (fine, smectitic, mesic Vertic Epiaqualfs) but with a deeper claypan (Chapter 3). The major species found in the prairie include big blue stem (*Andropogon genardi* Vitman.), little blue stem (*Schizachyrium scoparium* Nash.), prairie dropseed (*Sporobolus heterolepis* [A. Gray] A. Gray), and Indian grass (*Sorghastrum nutans* [L. J. Nash]) (Udawatta et al. 2008). Kucera et al. (1967) stated that the only sources of soil disturbances in prairies were fire, microbial processes, small rodents and insects.

Data Collection

Soil Data Collection Sampling was done during the summer of 2008 at both sites. Undisturbed soil cores of 7.6 cm (3 in) diam. and 7.6 cm (3 in) length were taken using an intact core sampler to determine soil water retention, bulk density and saturated hydraulic conductivity (K_{sat}). (Detailed data sampling scheme, and measurement techniques of soil hydraulic parameters was provided in Chapter 3, present dissertation). Apart from soil hydraulic properties, an order 1 soil survey (1: 5,000 scale) was done at the Field 1 site during 1993 and 1997 (Kitchen et al. 2005) and based on those results, soils were divided into seven different soil series (Figure 5.2) with each soil series having different soil properties (Table 6.1). The TP site soil properties, apart from soil physical properties that were measured during the study in Chapter 3, were collected from Udawatta et al. (2008).

Runoff Measurement and Sample Analysis A v-notch weir was constructed at the field outlet (Fig. 1) in 1991 and was instrumented with a runoff water stage recorder and a refrigerated automated pumping sampler (ISCO 3230, Teledyne Isco, Inc., Lincoln, Nebraska). The threshold value for triggering the runoff sample collection was 0.8 mm and it continued to collect samples through the runoff event. Then the samples were refrigerated, transported to the laboratory, and analyzed for atrazine [6-chloro-2-ethyl-4-(1-methylethyl)-1,3,5-triazine-2,4-diamine], dissolved nitrogen (NO_3-N), dissolved phosphorous (PO_4-P), and sediment. Details on the sampling and analysis methods were discussed in detail in Lerch et al. (2005) and Ghidey et al. (2010). The data collected from 1993 to 2001 were used for the present study including daily runoff, sediment, atrazine, dissolved nitrogen, and dissolved phosphorous loads.

Weather Data Measured daily rainfall and temperature data were available for the whole simulation period, from 1978 to 2007. An automated weather station was installed in the field in 1991 (Figure 6.1) with confirmed data in 1993 onwards, from which sub-daily rainfall (mm), temperature ($^{\circ}$C), average solar radiation (MJ m^{-2}), relative humidity (fraction), and wind speed (mm h^{-1}) data were collected, recorded and maintained in a server database managed by the USDA-ARS Cropping Systems & Water Quality Research Unit (CSWQRU) at the University of Missouri-Columbia (Sadler et al., 2006). Before 1991, these weather variables were statistically simulated by the model APEX, except rainfall and temperature; after 1990, all weather variables were available and used as inputs in the model. The annual average rainfall during the simulation period was 968 mm, and annual average maximum and minimum daily temperatures were 16.9 and 6.3 ^{o}C, respectively.

APEX Model Setup

The same calibrated and validated APEX model that was used in Chapter 5 was used for the present study. Field 1 was divided into 35 subareas based on homogenous soil type and depth to claypan (Figure 6.1). The model was calibrated and validated from 1993 to 2002 for measured runoff, sediment yield, and atrazine load at the Field 1 outlet. The efficiency values are provided in Table 6.2, and the APEX model was found to satisfactorily simulate these three measured variables.

Soil Loss Estimation Lerch et al. (2005) developed a historical soil depth map for Field 1, based on historical images and profile distributions of similar uncultivated soils. They also used a remote sensing technique for delineating the areas of variable topsoil losses based on the color representation in the imagery. Dark color soils were classified as un-eroded soils, light grey color pointed to where the E horizon was exposed, and red-orange areas indicated the exposed Bt horizon. Finally they developed a quadratic model based on the field topography ($R^2 = 0.66$) and quantified spatially distributed topsoil loss and deposition since the initiation of cultivation in Field 1. Soil loss or deposition areas in various parts of the field are shown in Figure 6.2.

Using the spatial distribution of soil loss/deposition for Field 1, the average soil loss or deposition was calculated with ArcInfo® for each subarea separately and this soil profile was assumed as the soil profile of Field 1 before the start of cultivation. This profile during the present study was called the ‘enhanced profile’, and the present soil profile after long-term cultivation on Field 1 was called the 'current profile'. It was assumed all the soil lost or deposited was from the topsoil of the first layer defined in the model APEX; therefore, during soil profile enhancement or reduction it was always done from the topsoil of each subarea, and the thickness of subsoil profiles were left unchanged except in one subarea 33 (Figure 6.1), where the soil deposition (28 cm) was more than the depth of first soil layer (25 cm) defined in the model after the start of agriculture, hence to create enhanced profile 3 cm were have to be reduced from the second soil layer (Table 6.3). The Table 6.3 shows the depth to claypan for current profile and enhanced profile for all of the subareas with soil loss or deposition. There were total 6 subareas with soil deposition after the start of agriculture and from rest of the 29 subareas there was soil loss. During the current profile scenario there were seven subareas with shallowest claypan depth (15 cm) in the field, in comparison to the only one during enhanced profile.

Variation between Field 1 and Tucker Prairie Soils The soil on the Field 1 has been redistributed since initiation of cultivation (Figure 6.2). Areas of soil erosion as well as some areas of deposition have significantly impacted the soil physical and chemical properties. The soil properties of TP that would be used as surrogate for Field 1 soil properties before the start of cultivation are shown in table 6.1. The maximum changes were observed in soil organic carbon (OC), saturated hydraulic conductivity (Ksat), and bulk density (BD). Organic carbon was 3.6% in TP surface soils as compared to the minimum value of 0.9% measured in Field 1, the surface Ksat was almost 100 times more for TP soil in comparison to the minimum value measured in the Field 1, and the BD for TP soil was less than 1 g cm^{-3} in comparison to a range of 1.3 to 1.5 g cm^{-3} in

Field 1. These changes in Bulk density and Ksat were caused by compaction at the Field 1 site because of agricultural trafficking, and in contrast better root distribution of native grasses in the TP soils (Chapter 3).

Scenario Analysis To study the impacts of long-term cultivation on runoff, sediment yield, atrazine load and crop yield, four different soil input simulation scenarios were designed: 1) Field 1 current profile with Field 1 soil properties (base line; CPF1), 2) enhanced profile with Field 1 soil properties (EPF1), 3) current soil profile withTucker Prairie (TP) soil properties (CPTP), and 4) enhanced soil profile with TP soil properties (EPTP). Other than the soil profile and soil properties, all other model parameters were kept the same for all the scenarios. The crop management for the thirty year simulation for all scenarios was a corn-soybean rotation with mulch tillage. The corn crop was cultivated during even years and was planted in May and harvested in October. Nitrogen and phosphorous fertilizers were applied before sowing together with atrazine herbicide. These inputs were incorporated during a mulch tillage operation. During the odd years of the simulation, the soybean crop was also planted and harvested in May and October, respectively, with no agricultural inputs.

Statistical analysis was performed using a t-test with the PROC GLM procedure (SAS Institute, 1999) at the 90 % significance level to test differences between annual average simulated runoff, sediment yield, atrazine load, and crop yield for the four scenarios. The differences between scenarios were only because of soil profiles and soil properties, i.e. differences between CPF1 and EPF1 and between CPTP and EPTP would provide the impact of soil thickness on all selected model outputs (runoff, sediment yield, atrazine load, and crop yield). On the other hand, differences between CPF1 and CPTP and between EPF1 and EPTP would provide information on the variations in selected model outputs only because of soil properties. In the end, the differences between scenarios CPF1 and EPTP would give an insight on how long-term cultivation had affected the selected model outputs.

Results

APEX Model Simulation Scenario Analysis

The average annual results of runoff, sediment yield, atrazine load and crop yield for the total thirty year simulation period are presented in Table 6.4. As expected the EPTP scenario generated lower amounts of surface runoff, sediment yield, and atrazine load but only the reduction in atrazine load was found to be significant than the CPF1 scenario. The scenario with an enhanced profile and Field 1 soil properties (EPF1) had outputs similar to those for CPF1, and CPTP had outputs similar to those of EPTP. There were no significant differences in annual average surface runoff generated among the four different scenarios. Similarly, there was no significant reduction in average annual sediment yield for any scenario with respect to the baseline. However, there were significant reductions in atrazine load and increases in soybean yields generated by scenarios CPTP and EPTP, i.e., with TP soil properties, in comparison to those with Field 1 soil properties. For corn, only the last scenario, with an enhanced profile and TP soil properties, produced significantly higher yields than the baseline.

The results were further evaluated for dry and wet years. The 30 simulated annual runoff and sediment yield values were divided into those that corresponded to the six years with highest rainfall (wet years) and the six years with lowest rainfall (dry years). For soybean yield (odd years) and corn yield and atrazine load (even years), the simulated results were available for only 15 years. From these fifteen years, the five years with maximum rainfall were treated as wet years and the five years with minimum rainfall were treated as dry years, separately for the even and odd years (corn vs. soybean).

Runoff and sediment yield variations during wet and dry years are shown in Figure 6.3. The trends of runoff and sediment yield for all the four scenarios during both periods were found to be similar. The difference in average annual runoff between baseline (CPF1) and EPTP scenarios were 11 and 9% during wet and dry periods, respectively. Similarly, the average annual difference in sediment yield between the two extreme scenarios CPF1 and EPTP for wet and dry periods were almost negligible (<0.01%). The atrazine load variations were found to be dependent on wet and dry periods as shown in Figure 6.4. During wet years, there was a reduction in average annual atrazine load of 84% in comparison to 65% during the dry years. These differences of average annual atrazine load between wet and dry years were similar for all four scenarios.

Crop yield variations for the whole field during wet and dry periods are shown in Figure 6.5. Variations in corn yield caused by the soil profile or the soil properties during wet years were less than during the dry period; however, it was found that corn yield was most variable among scenarios during average rainfall years. The average increase in corn yields from the CPF1 to EPTP scenario during wet and dry periods were 24 and 40%, respectively, while it was 50% for the average rainfall period. The soybean yields were found to be most affected by soil profile and properties during wet periods, the average increases in yield from the CPTP to EPTP scenario during wet and dry periods were 111 and 57%, respectively; during average rainfall years, the increase was only 29%.

Spatial Variability

The two extreme scenarios, CPF1 and EPTP, are representative of the variations caused by long-term cultivation in comparison to native soils. These scenarios were also analyzed for spatial variations in simulated outputs. These conditions led to different critical areas that generate higher amounts of runoff (Figure 6.6) and atrazine load (Figure 6.7) in comparison to the EPTP scenario indicative of the site that has never been cultivated. The spatial variations in corn yield (Figure 6.8) and soybean yield (Figure 6.9) as well as sediment yield (figure 6.10) were almost similar in both scenarios, but the magnitude of values varied.

More than half of the field (51%) was generating higher runoff during scenario CPF1 than the maximum amount of runoff generated by scenario EPTP (249 mm), and 20% of the field was generating lower runoff in scenario EPTP than the lowest amount of runoff generated by scenario CPF1 (184 mm; Figure 6.6). Even though the total amount of runoff was not significantly different at the watershed outlet, there was greater amount of area generating higher runoff. The areas that were generating higher amounts of runoff in the current state of the field were on the backslope positions of the field whereas for the EPTP scenario, the highest runoff class was on the outer boundary of the field, i.e., the summit position. The spatial variation of atrazine load generated by the field during the CPF1 scenario was higher than the variation for the EPTP scenario (Figure 6.7).

The corn yield was significantly higher during scenario EPTP in comparison to the CPF1 scenario, 31% of field area was producing higher corn yield for scenario EPTP than the highest corn yield (5.2 t ha^{-1}) produced during the CPF1 scenario (Figure 6.8). Similarly for soybean yield, 40% of field area was producing higher yield than the highest soybean yield (1.4 t ha^{-1}) produced during the CPF1 scenario (Figure 6.9). The sediment yield spatial distribution showed that during EPTP scenario, 9% of the area was yielding higher amounts of sediments than the maximum amount of sediment generated during scenario CPF1, but 21% of the area was also generating lower amounts than the minimum amount generated during scenario CPF1 (Figure 6.10).

Discussion

Runoff and Sediment Yield

There were no significant changes found in total sediment yield or runoff in any of the scenarios compared to the baseline. Sediment loss depends upon the spatial scale considered, which depends upon the field size and whether depositional regions of the field are or are not considered (Lal, 2001). In this field, while there were regions of soil loss, there were also areas with soil deposition occurring during the 100 years of cultivation (Figure 6.2). The highest sediment loss occurred during scenario EPTP (Figure 6.10) in areas just upstream to the areas where maximum deposition occurred (Figure 6.2). Therefore, net sediment loss from the field did not change significantly.

The net amount of simulated runoff at the field outlet was not significantly changed among the scenarios. The spatial variation in runoff was found to be considerably changed; in both the scenarios EPTP and CPTP the subareas with the shallowest depth to claypan had the highest amount of surface runoff (Figure 6.6). In scenario CPF1, it was the backslope positions and in scenario EPTP it was the outer boundaries of the field. It was found the areas that were more eroded during long-term cultivation (Figure 6.2) tended to generated higher surface runoff in current conditions. The other thing that was observed, with the increase in surface soil thickness there was also an increase in lateral flow from the field, therefore the net change in runoff at the watershed outlet was insignificant.

The study in Chapter 5 showed significant reductions in runoff and sediment yield when the backslope areas in CPF1 scenario were managed under switchgrass (*Panicum virgatum L.*) for 30 years. Given the lack of significant reduction caused by changes in soil profile or soil properties, it was concluded that land management has more impact on runoff and sediment yields than differences in soil quality. The soil loss in the APEX model was estimated using the theoretically developed equation MUST (Modified Universal Soil Loss Equation Theoretically developed; Williams et al. 2006) which was found to have the best results in the field. This equation considers six different factors for soil loss estimation. Five of the factors were similar for all of the scenarios, i.e., runoff factor based on amount of runoff volume and peak flow (X), crop management factor (CVF), erosion control factor (PE), the coarse fragment factor (ROKF).and slope and steepness factor (SL). The soil erodibility factor (EK) was the only parameter that varied among the scenarios and was the reason for sediment loss variation between scenarios. The EK is dependent upon soil texture and soil organic matter. In this case, the only factor that was variable was the soil organic matter (SOM), which reduces soil erosion as it increases (Steglich and Williams, 2008). In comparison, the change in management is reflected in two factors, CVF and PE and could be the reason for higher reductions in sediment losses caused by management rather than soil properties.

Erosion started when agriculture was first initiated in this field and, assuming similar management, the erosion rates would have been similar to the current ones. During the present study the 30 year annual average simulated soil loss from field for scenario CPF1 was 7.6 t ha^{-1} (Table 6.4), if we assume average soil density of 2.65 g cm^{-3} the total soil loss from the field after 100 years would be around 3 to 4 cm. Whereas, the study in chapter 3 shows the topsoil thickness difference between the field and the TP site was about 20 to 30 cm and even figure 6.2 suggests the same magnitude of soil loss from the field. This could be attributed to the early cultivation practices resulting in soil erosion rates that may have been higher. This has been documented with the reduction in the intensity of tillage the soil loss also reduces (Laflen et al., 1978; Johnson and Moldenhauer, 1979; Lindstrom et al., 1992; Tebrugge and During, 1999). Early agriculture relied on tillage much more than now, for present simulation during all the scenarios the field was under mulch tillage, whereas, the history of field management suggests the use of moldboard plow till the later part of twentieth century (Lerch et al. 2005).

Atrazine Load

The variation in simulated atrazine load showed there was significant reduction when the soil properties were changed from Field 1 to TP, but not when soil profile thickness was varied from the current profile to an enhanced profile. For each set of soil properties, the scenarios had similar annual average atrazine loads in spite of variations in soil thickness (Table 6.4). The increase in SOM content in scenarios EPTP and CPTP in comparison to the scenarios CPF1 and EPF1 could be one of the factors for the simulated atrazine reduction. The increase in SOM increases the adsorption of atrazine to the soil

(Barriuso et al. 1992; Laird et al. 1994; Piccolo et al. 1998). This process was simulated in the APEX model by adjusting the partition coefficient (KD) of atrazine as a function of the SOM, with an increase in SOM causing an increase in KD and more atrazine adsorbing to the soil (Steglich and Williams, 2008). Given the measured values of SOM in TP and Field1, the KD value for surface soil of TP was 7.2 while it was 1.8 for the Mexico soil series in Field 1. Therefore the reduction in SOM after long-term agriculture was one of the main factors in higher atrazine loads at the field outlet.

During the wet years there was more atrazine loss in the CPF1 and EPF1 scenarios in comparison to the other two (Figure 6.4). Because of the increase in rainfall there was more opportunity for transport of dissolved atrazine with runoff, whereas during the dry years, this was not the case. Except year 2002, even though it was a dry year, there was a steep increase in simulated atrazine load at the field outlet (Figure 6.4), because 55 mm of rainfall occurred three days after the atrazine application. The scenario EPTP had reduced atrazine loads even during extreme events like this in comparison to CPTP scenarios. Overall with better soil quality and improved SOM content, there was a lower amount of atrazine loss at the field outlet.

Crop Yield

The corn and soybean yields were significantly reduced with soil properties and a soil profile resulting from 100 years of cultivation. The corn yields were significantly higher only during the scenario EPTP (Table 6.4); this means better corn yields not only need adequate top soil (enhanced soil profile) but also improved soil properties. On the other hand, soybean yields were significantly improved when there was an increase in top soil thickness, even with the current Field 1 soil properties. The reason could be that corn yields are more sensitive to fertilizer and water stress in comparison to soybean crops (Thompson et al. 1991; Kitchen et al. 2005b). For these reasons, the corn crop was most affected during average and dry rainfall years, and least affected during wet periods (Figure 6.5). Possibly during low rainfall years, the increased topsoil thickness maintained a sufficient amount of moisture in comparison to the eroded top soil scenarios. The soybean yield was less dependent upon wet or dry periods but yields were higher for EPTP and CPTP scenarios during all years.

The spatial distributions of both crop yields were similar during the two extreme scenarios (EPTP and CPF1; Figures 6.8 and 6.9). The only differences were in the absolute yields per subarea that were higher for more subareas during the EPTP scenario in comparison to the CPF1 scenario.

Conclusions

The present simulation study was done to simulate and analyze the impact of long-term agricultural production and associated deterioration of soil quality on runoff, sediment yield, atrazine load, and corn and soybean yields in a field (Field 1) with claypan soils. Using two sets of soil profiles and soil properties, four simulation scenarios were developed to represent current conditions, original or enhanced conditions, and two alternative states that correspond to the improvement of the soil properties and the increase of the top soil depth relative to current conditions. Two extreme scenarios were enhanced soil profile and improved soil properties (EPTP) representative of field that has never been cultivated and current profile with current soil properties (CPTP) representative of field under long-term cultivation.

A calibrated and validated APEX (Agricultural Policy Environmental eXtender) model for daily runoff, sediment yield, and atrazine load was used to simulate the four scenarios under a corn-soybean rotation with mulch tillage. Then, the model was run for thirty years (1978 to 2007) with measured weather data for simulating the selected outputs (runoff, sediment yield, atrazine load, and corn and soybean yields) and average annual outputs were compared to analyze the impact of long-term agriculture.

Based on thirty year (1978-2007) simulations, average annual atrazine load was reduced and average annual soybean yield was increased significantly for scenarios with enhanced soil properties in comparison to the baseline. The corn yield was significantly increased only with original conditions in comparison to the baseline. On the other hand, there was no significant reduction found in surface runoff and sediment yield for any of the scenarios in comparison to the baseline, but the scenario with current soil properties and profile had 51% of field area generating more runoff than the maximum runoff generated by the scenario with enhanced soil profile and improved soil properties.

The reduction in EPTP scenario atrazine load in comparison to baseline (CPF1) was 84% during wet years and 65% for dry years. The improved soil quality also did tend to reduce the atrazine load for runoff events occurring shortly after the atrazine application in the field. The spatial patterns of atrazine losses were different for the field during the scenarios EPTP and CPF1. The areas that were losing more soil because of soil erosion over the long period of cultivation were shown to become more critical for surface runoff. On the other hand, areas producing higher soil losses after long-term cultivation were similar to those identified with initial soil conditions. This study shows that improvement of soil conditions would not reduce simulated erosion significantly because of the lower dependence of erosion on soil properties instead of management.

With the EPTP scenario, we attempted to represent the field soil conditions when it was first cultivated but with current management practices. This scenario produced on average 40% higher corn and 39% higher soybean yields in comparison to the field after cultivation for over 100 years (scenario CPF1). The corn yield differences were higher during the rainfall periods classified as average and dry in comparison to the wet periods. It was found with improved soil properties, the corn yield was more resistant to water stress. Earlier producers probably saw less variation in yields caused by variation in rainfall. On the other hand, soybean yields were found to outperform during all types of rainfall years in the scenario EPTP with respect to the baseline.

Based on these results, we conclude that the restoration of soil physical and chemical properties not only would increase crop yields but also reduce the atrazine losses at the field outlet. The runoff and sediment losses were found to be more dependent on the current ground cover and management rather than just on improved soil properties, but the amount of area generating higher amounts of runoff and sediment yield tends to increase with the span of time of cultivation on a field.

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Tables

Table 6. 1: Surface soil properties of Field 1 and TP sites.

Soil Series	Surface Soil Properties							Claypan Depth Range (cm)
	Organic C (%)	pH	Cation Exchange Capacity (CEC; c mol/g)	Ksat (mm/h)	BD (g/cm^3)	Texture (%)		
						Silt	Clay	
Field 1								
Adco	1.1	5.8	21.7	47.7	1.4	72.4	21.9	15 - 38
Argialboll	1.2	5.7	19.8	136.3	1.4	71.0	23.8	30 - 55
Argiaquolls	1.2	5.0	18.5	12.5	1.3	79.3	20.2	60 - 100
Leonard	1.0	5.8	17.1	3.4	1.5	70.1	18.7	25 - 53
Mexico	0.9	5.6	19.4	5.6	1.4	78.3	16.2	15 - 40
Putnam	1.3	5.0	20.1	153.1	1.4	70.4	23.2	30
Average Surface Soil Properties Tucker Prairie site								
TP Soil	3.6*	5.2*	19.3*	315.9	0.81	74.3*	18.9*	41

* Source Udawatta et al. (2008)

Table 6. 2: Monthly calibration and validation efficiency values for three model outputs.

Model Outputs	Calibration (1993 to 1997)			Validation (1998 to 2002)		
	r^2	NSE	Pbias (%)	r^2	NSE	Pbias (%)
Runoff	0.74	0.72	-2.20	0.69	0.68	-0.80
Sediment Yield	0.50	0.49	-1.90	0.53	0.36	-50.10
Atrazine Load	0.75	0.62	5.43	0.61	0.61	17.70

Table 6. 3: Soil loss and deposition in Field 1 after initiation of cultivation around 100 years ago. Current profile: the first soil layer depth defined in model APEX after long-term cultivation, and Enhanced profile: the first soil layer depth defined in model APEX for the Field 1 before the initiation of agriculture.

Subarea	Depth to Claypan (Current Profile; cm)	Depth to claypan (Enhanced Profile; cm)	Soil Series
1	30	33 (3)*	Putnam
2	25	26 (1)	Adco
3	38	41 (3)	Adco
4	25	45 (20)	Mexico
5	40	29 (-14)	Leonard
6	38	37 (-1)	Adco
7	15	16 (1)	Adco
8	38	39 (1)	Adco
9	15	15 (0)	Adco
10	38	58 (20)	Adco
11	25	29 (4)	Adco
12	15	38 (23)	Mexico
13	30	58 (28)	Argialbolls
14	38	49 (11)	Adco
15	25	36 (11)	Leonard
16	38	56 (18)	Adco
17	40	69 (29)	Mexico
18	40	73 (33)	Leonard
19	55	57 (2)	Argialbolls
20	15	28 (13)	Adco
21	25	46 (31)	Leonard
22	25	38 (13)	Adco
23	40	54 (14)	Mexico
24	25	61 (36)	Leonard
25	55	48 (-7)	Argialbolls
26	15	52 (37)	Adco
27	15	45 (30)	Mexico
28	40	70 (30)	Mexico
29	25	29 (4)	Leonard
30	60	56 (-4)	Argiaquolls
31	23	42 (19)	Leonard
32	25	56 (31)	Leonard
33	100	72 (-28)	Argiaquolls
34	15	36 (16)	Mexico
35	60	56 (-4)	Argiaquolls

* In parentheses total amount of soil loss (+ve) and deposition (-ve) occurred.

Table 6. 4: Thirty year average annual simulated values for four different scenarios; (i) CPF1: Current soil profile depth with Field 1 properties (Baseline), (ii) EPF1: Enhanced soil profile depth with Field 1 properties, (iii) CPTP: Current soil profile depth with Tucker Prairie properties, and (iv) EPTP: Enhanced soil profile depth with Tucker Prairie properties.

Scenario	Runoff (mm)	Sediment Yield (t/ha)	Atrazine Load (g/ha)	Corn Yield (t/ha)	Soybean Yield (t/ha)
CPF1	241 (a)*	7.6 (a)	9.4 (a)	2.8 (a)	0.8 (a)
EPF1	240 (a)	7.3 (a)	9.2 (a)	3.1 (a)	0.9 (a)
CPTP	203 (a)	7.3 (a)	1.7 (b)	3.6 (ab)	1.3 (b)
EPTP	211 (a)	6.9 (a)	1.7 (b)	3.9 (b)	1.4 (b)

* Values with different letters were found to be significantly different ($P < 0.05$) in the same row.

Figures

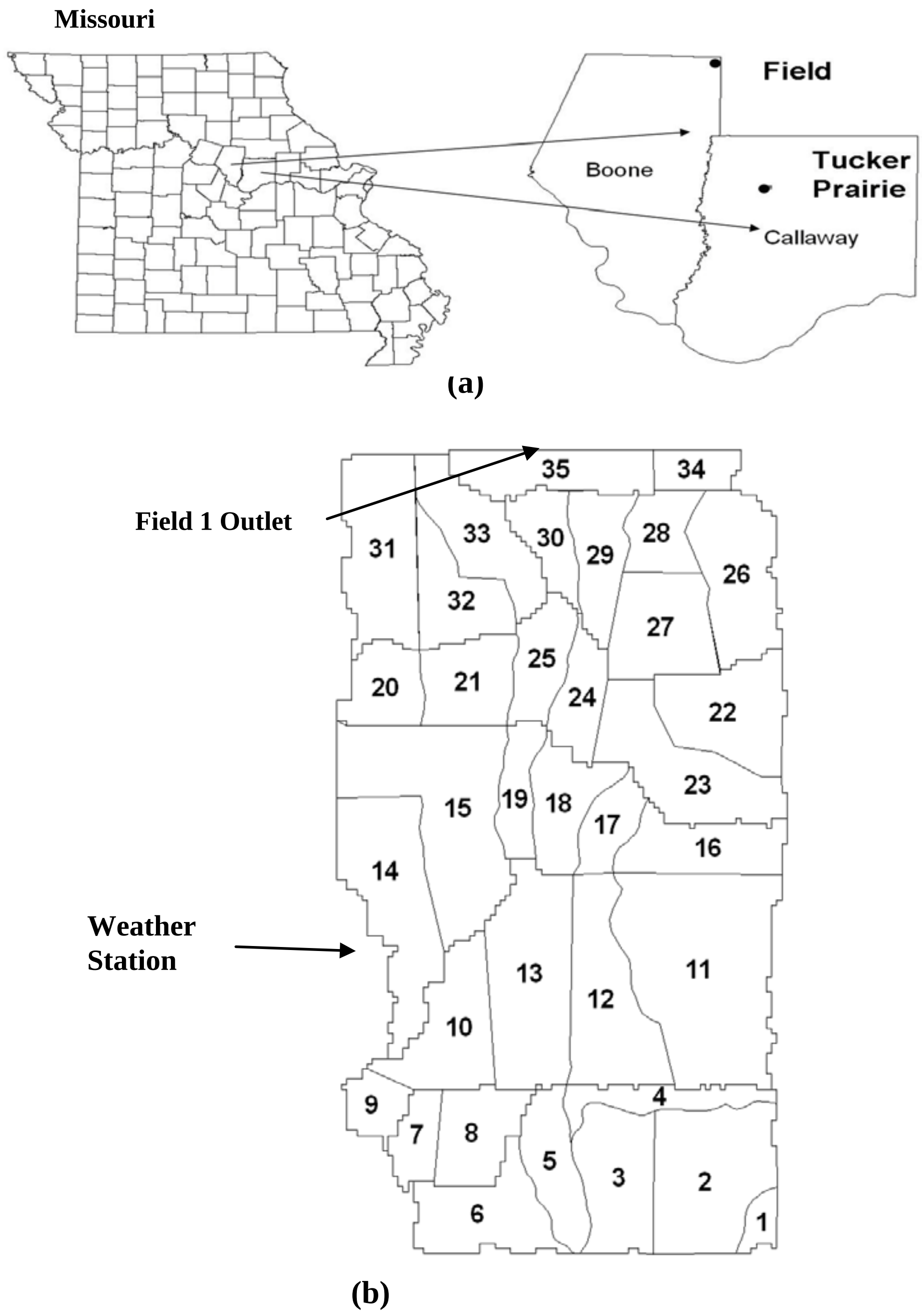
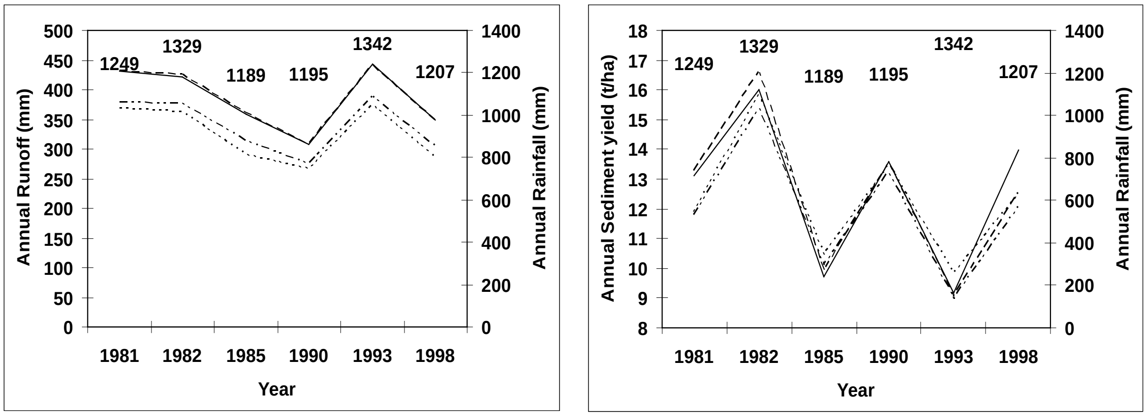


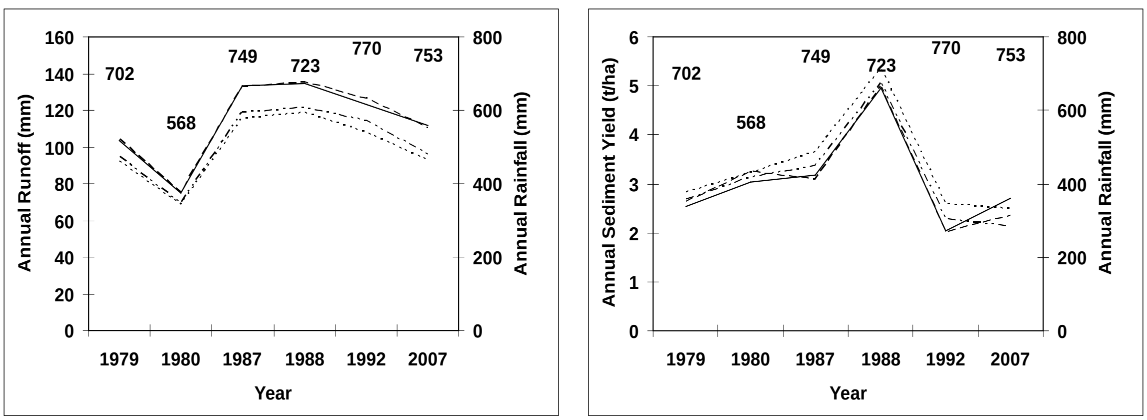
Figure 6. 1: (a) Location of study sites, Field 1 (39º 13' 48"N, 92º 7' 12" W), and Tucker Prairie (38º 57' 4" N, 91º 59' 30" W). (b) Field 1 divided into 35 different subareas with each subarea having homogenous depth to claypan and soil type.

Figure 6. 2: Soil loss and deposition in Field 1 after initiation of cultivation around 100 years ago.

(a) Wet Years



(b) Dry Years



——— **CPF1: Current Profile Field 1 soil properties**

······ **CPTP: Current Profile Tucker Prairie soil properties**

– – – – **EPF1: Enhanced Profile Field 1 soil properties**

–·–·– **EPTP: Enhanced Profile Tucker Prairie soil properties**

Figure 6. 3: Annual variation in simulated runoff (mm) and sediment yield (t/ha), (a) during six wettest years, and (b) during six driest years.

(a) Wet Years **(b) Dry Years**

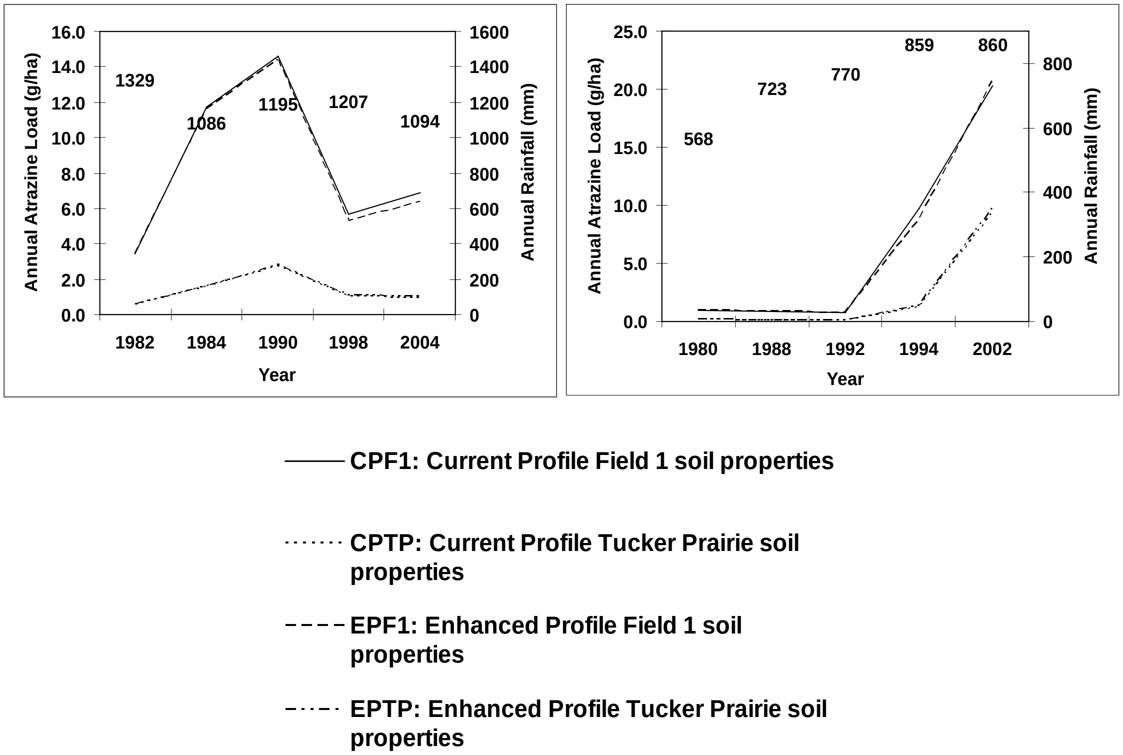


Figure 6. 4: Annual variation in simulated atrazine load (g/ha), (a) during five wettest years, and (b) during five driest years.

(a) Wet Years

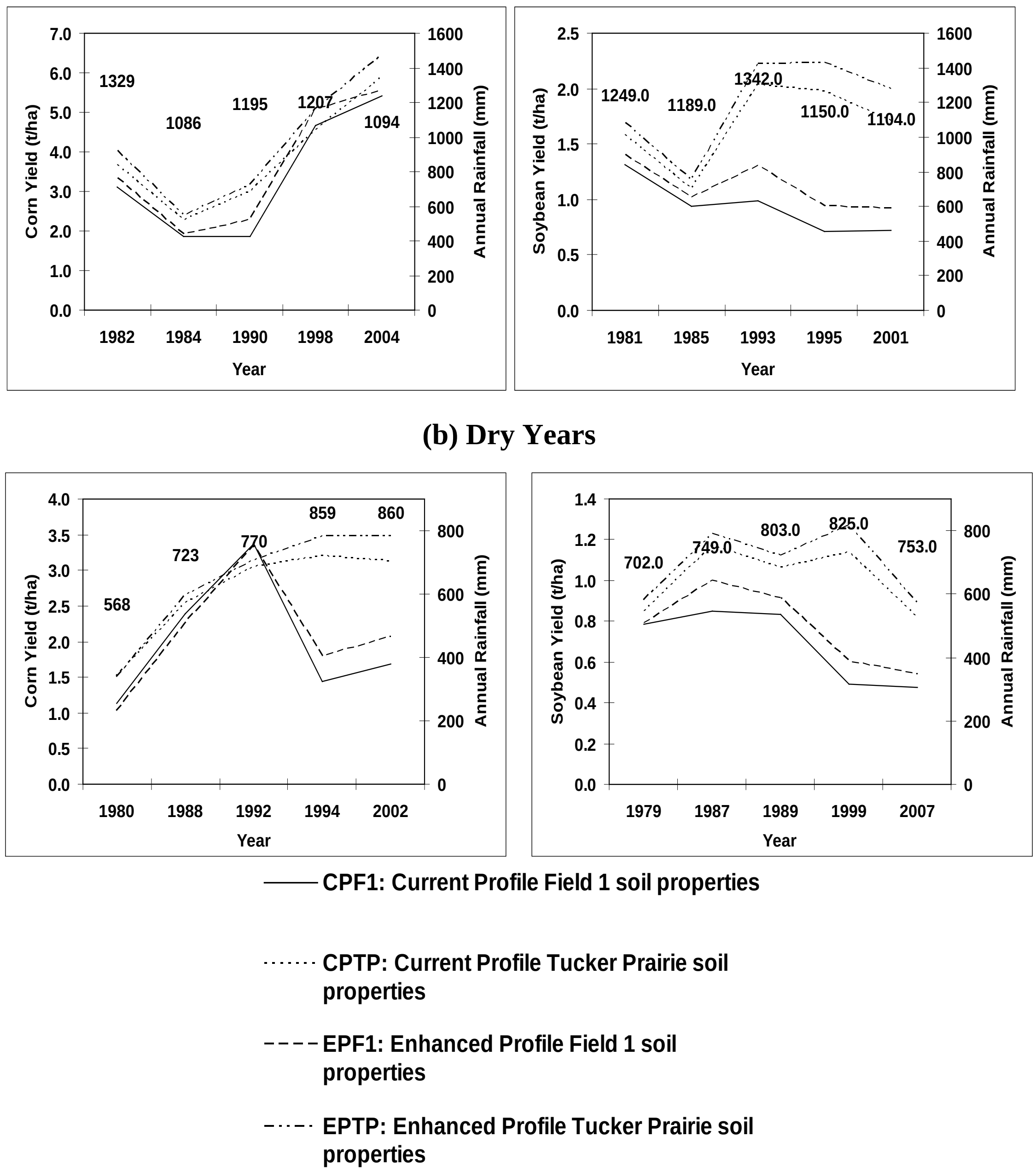


Figure 6. 5: Annual variation in simulated corn and soybean yields (t/ha), (a) during five wettest years, and (b) during five driest years.

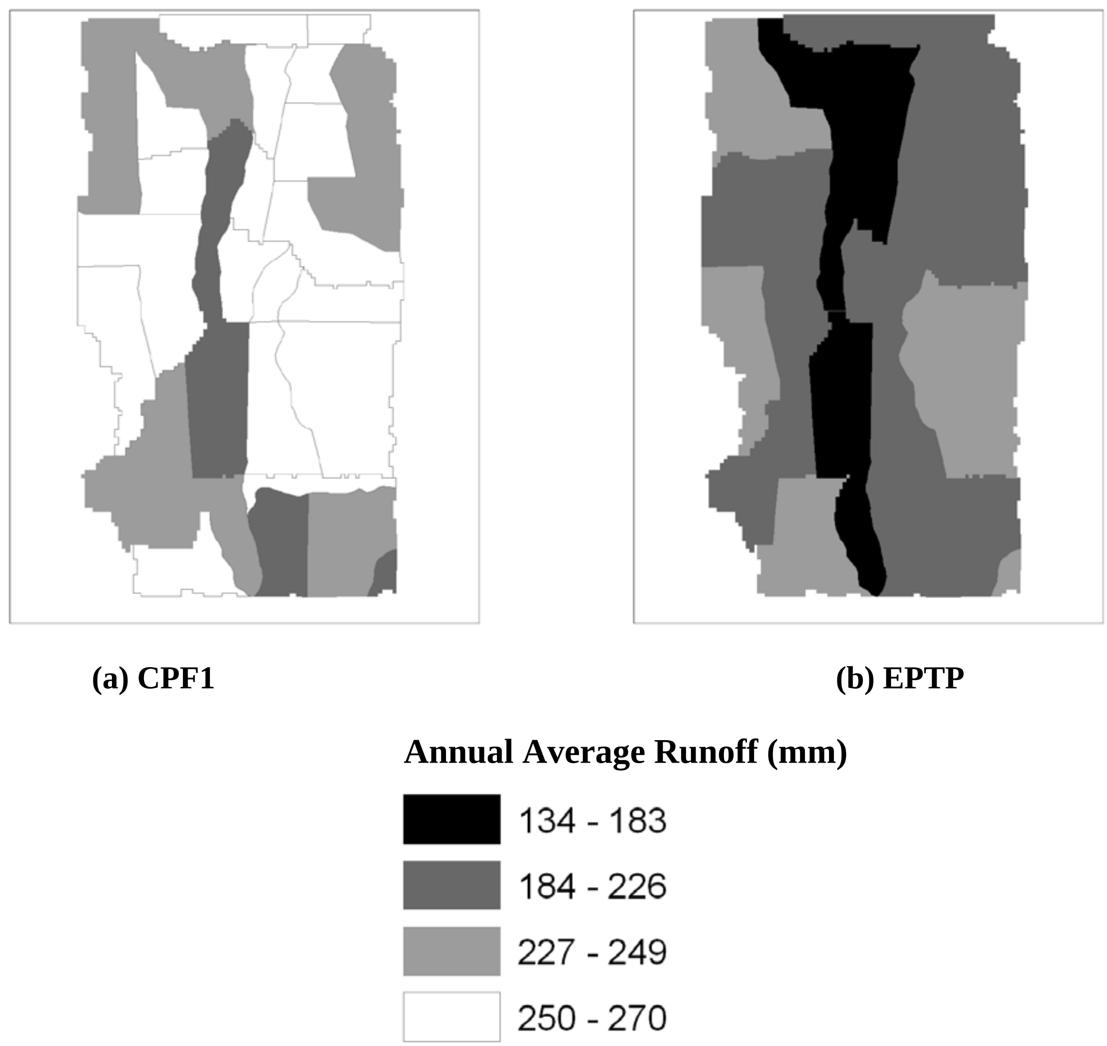


Figure 6. 6: Annual average spatial variation of simulated runoff (mm) by subareas for thirty years (1978 to 2007), (a) Scenario CPF1: Current profile and Field 1 soil properties, and (b) Scenario EPTP: Enhanced profile and Tucker Prairie soil properties.

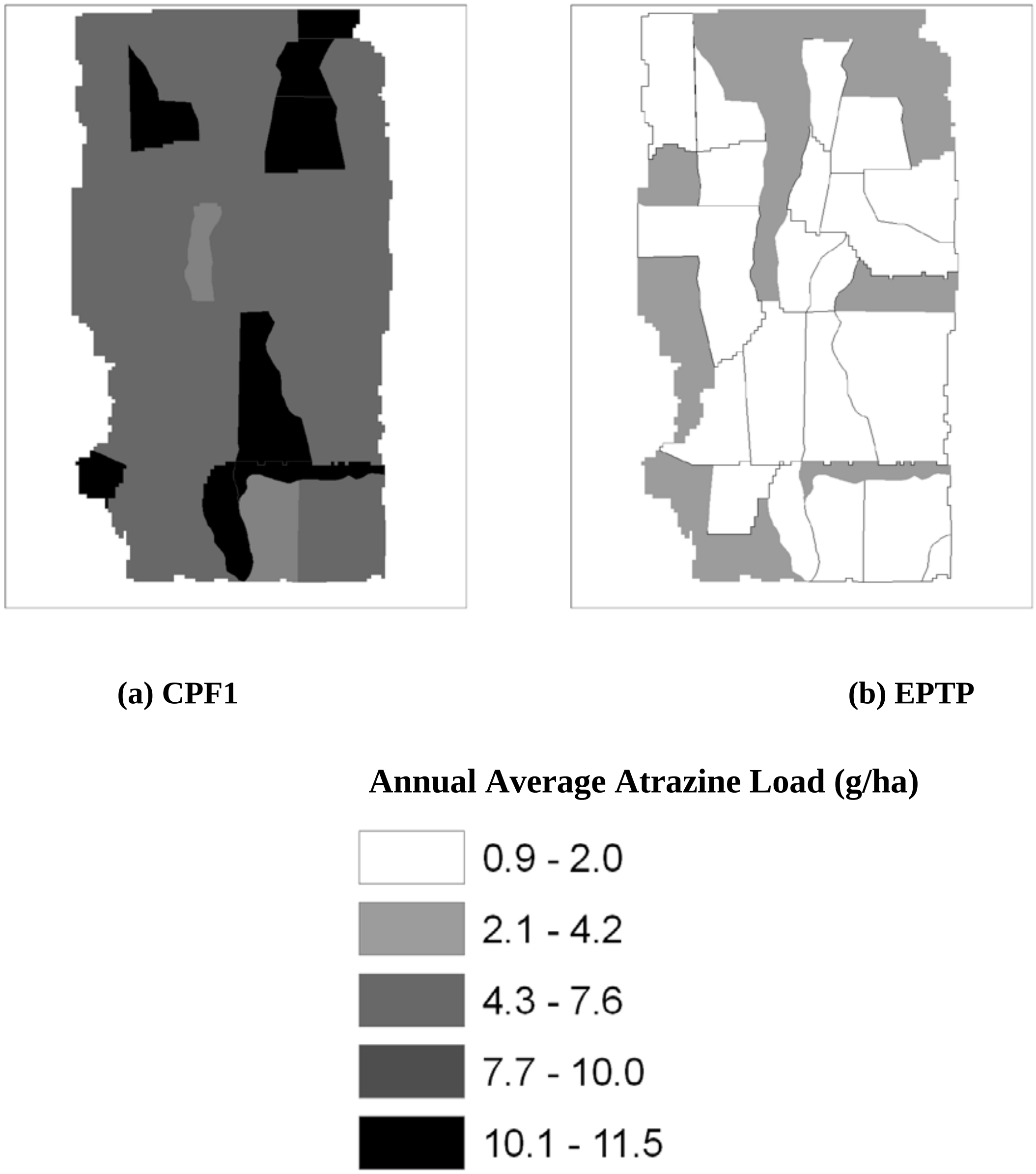


Figure 6. 7: Annual average spatial variation of simulated atrazine load (g/ha) by subareas for thirty years (1978 to 2007), (a) Scenario CPF1: Current profile and Field 1 soil properties, and (b) Scenario EPTP: Enhanced profile and Tucker Prairie soil properties.

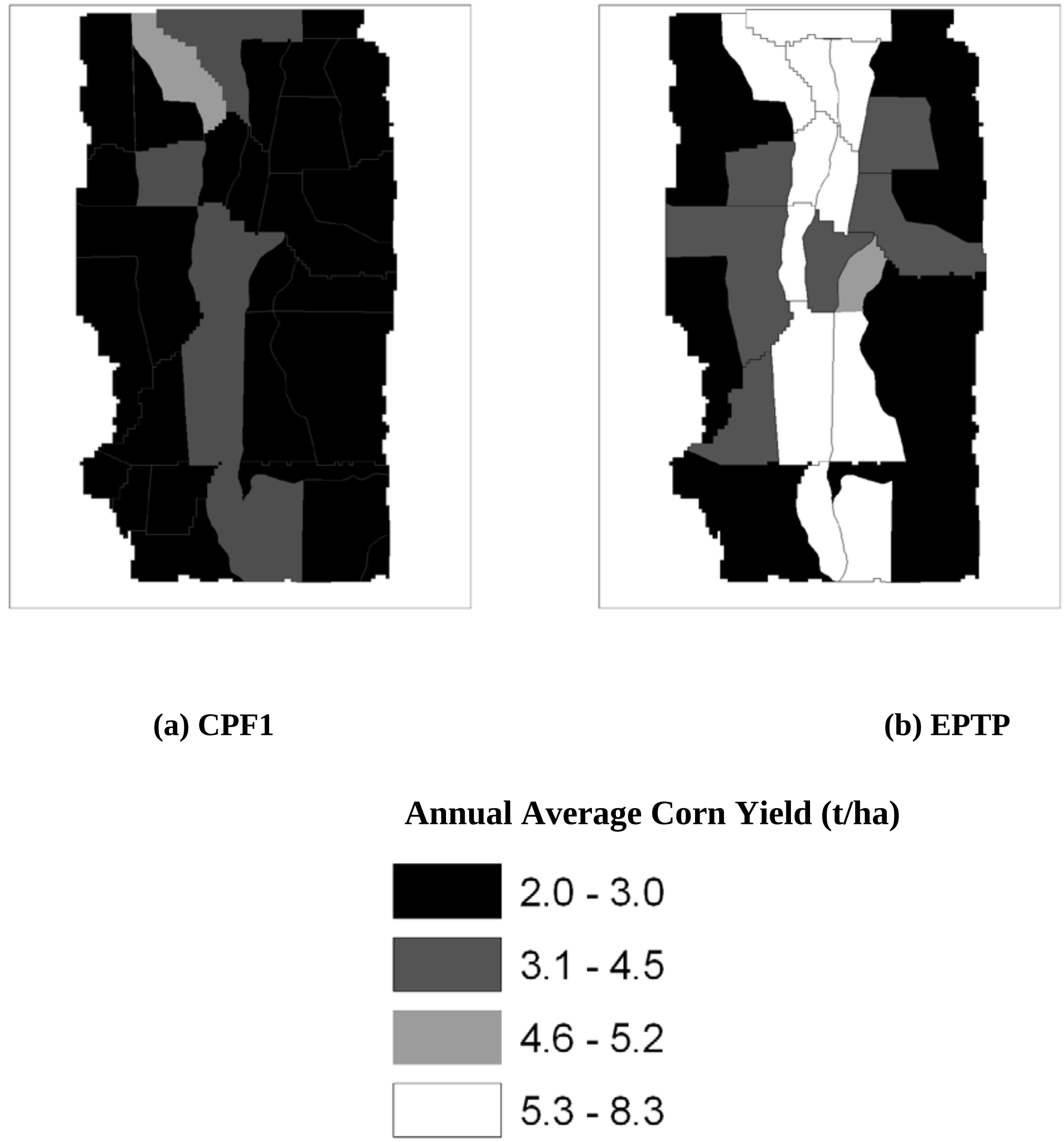


Figure 6. 8: Annual average spatial variation of corn yield (t/ha) by subareas for thirty years (1978 to 2007), (a) Scenario CPF1: Current profile and Field 1 soil properties, and (b) Scenario EPTP: Enhanced profile and Tucker Prairie soil properties.

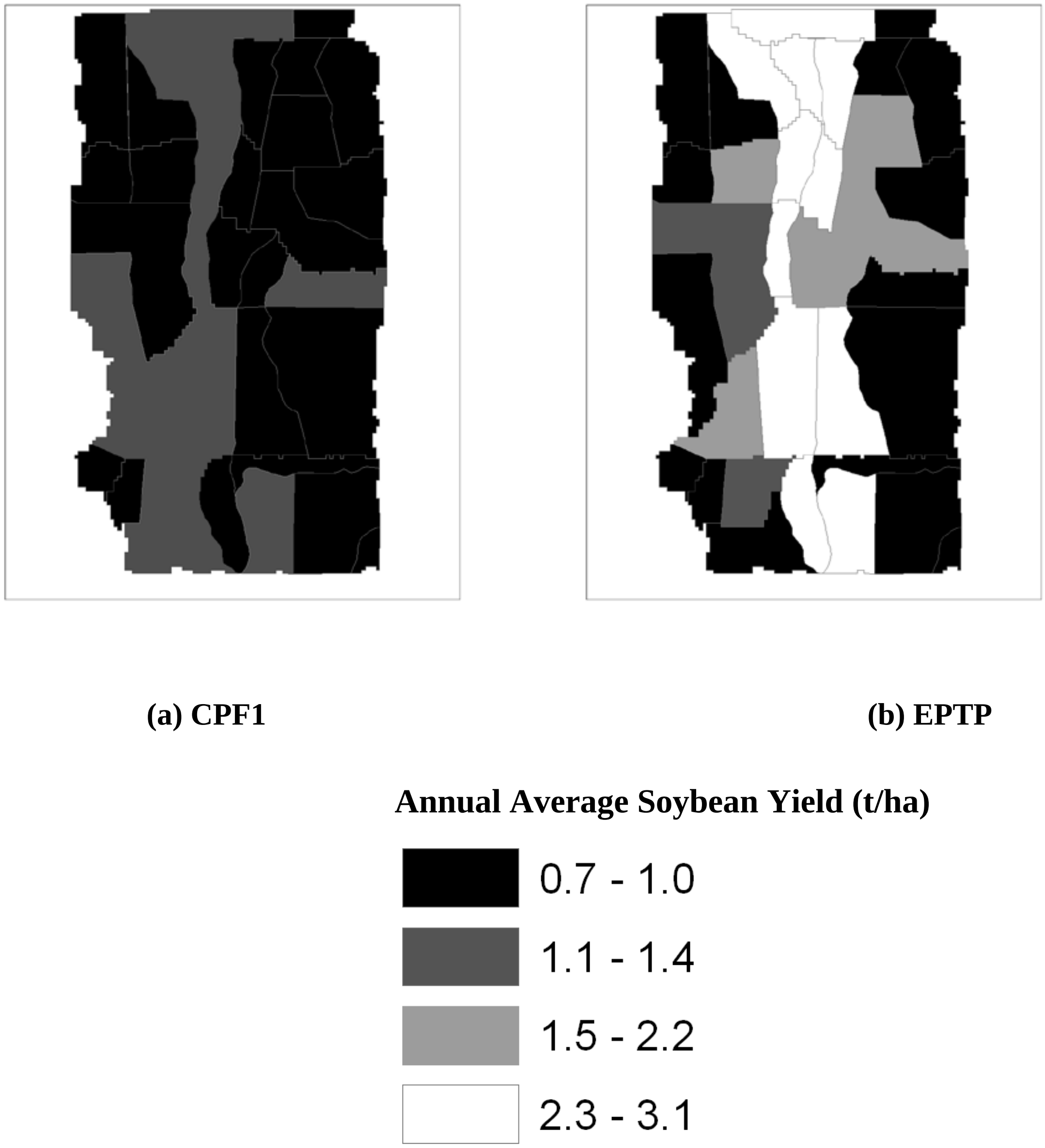


Figure 6. 9: Annual average spatial variation of soybean yield (t/ha) by subareas for thirty years (1978 to 2007), (a) Scenario CPF1: Current profile and Field 1 soil properties, and (b) Scenario EPTP: Enhanced profile and Tucker Prairie soil properties.

(a) CPF1 **(b) EPTP**

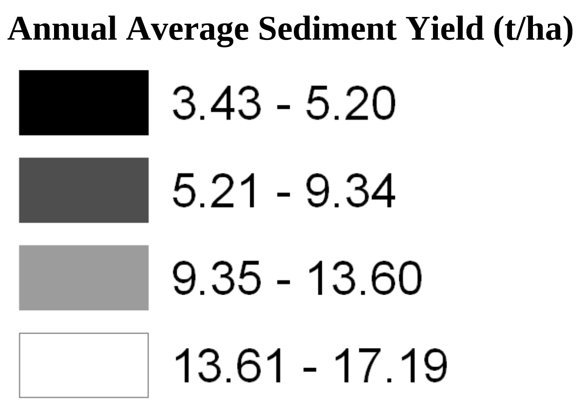


Figure 6. 10: Annual average spatial variation of sediment yield (t/ha) by subareas for thirty years (1978 to 2007), (a) Scenario CPF1: Current profile and Field 1 soil properties, and (b) Scenario EPTP: Enhanced profile and Tucker Prairie soil properties.

CHAPTER 7

DELINEATION OF CRITICAL MANAGEMENT AREAS IN THE GOODWATER CREEK WATERSHED USING TWO INDICES

Abstract

Watersheds have areas that are more critical relative to soil and water quality deterioration and have a pronounced effect on water quality at downstream sites. The present study was conducted to delineate these critical management areas (CMAs) in the Goodwater Creek Experimental Watershed (GCEW) characterized by claypan soils with a high potential for runoff and generation of non-point source pollutants, and to simulate effects of placement of best management practices (BMPs) in these CMAs. Two indices, the Conductivity Claypan Index (CCI; CD*Ksat /SL) and the Claypan Index (CPI; CD/SL) estimated from Ksat, the surface saturated hydraulic conductivity; CD, the depth to the claypan; and SL, the average slope, were used to delineate CMAs in the watershed. Twenty-five percent of the total watershed area under agricultural land use had the lowest values of CCI and CPI and were treated as CMAs. The SWAT model, satisfactorily calibrated and validated for streamflow, sediment yield, phosphorus load and atrazine load for the GCEW, was used to confirm the reliability of the CMAs delineated with CCI and CPI, calculated for each Hydrological Response Unit (HRU). The coefficients of correlation (*r*) found between selected annual average model outputs generated from each HRU and the index values for those areas indicated significant relationships. Significant correlations were found for both indices with surface runoff, lateral flow, sediment yield, and sorbed nutrients generated from those areas. Furthermore if the model outputs were

broken down by management practices, the *r* values became stronger. The annual average crop yields were not directly correlated with the index values but the CMAs had higher number of days with water and nutrient stresses which correlated well with the indices. Therefore, the indices CPI and CCI, in conjunction with knowledge of current management practices, could be a less costly and time consuming method to delineate CMAs in watersheds with claypan soils. These delineated CMAs were placed under three different scenarios with BMPs: filter strips (FS), grassed waterways (GWW), and terraces. Thirty year model simulations with the scenarios showed significant reductions in simulated sediment yields (51 to 54%) and phosphorus loads (19 to 23%). Targeting CMAs with BMPs delineated using the CCI and CPI indices can be an effective way to reduce the sediment and phosphorus loads from the GCEW.

Introduction

The Conservation Effects Assessment Project (CEAP) was initiated to study the impact of various environmental conservation practices on water and soil quality (Duriancik et al., 2008). To analyze the regional impacts on environment in CEAP, the USDA-Agricultural Research Service (ARS) established 14 research watershed sites throughout the US (benchmark watersheds). One of the benchmark watersheds is the Salt River Basin (6, 417 km^2) in northeast Missouri that drains into the Mark Twain Lake (Figure 7.1), which is the major source of drinking water in the region (Lerch et al., 2008). This watershed is characterized by claypan soils that have a high potential for generating surface runoff, and non-point source pollutants especially after their immediate application (Ghidey et al., 1997; Ghidey and Alberts, 1999; Kitchen et al., 2005, Lerch et al., 2005). Claypan soils have an abrupt boundary to a subsoil argillic horizon that sometimes have clay contents almost 100% higher than the above soil layer (Myers et al., 2007). Along with its environmental impacts, this claypan horizon tends to negatively affect crop yields in the region during dry to average rainfall years (Chapter 6; Kitchen et al., 2005).

Accelerated soil erosion during the last century was a major factor in deterioration of topsoil and manifestation of shallow claypans in this region. Lerch et al. (2008) depicted the history of the Salt River watershed and suggested the increased pace of human settlement in this region during the early 19^{th} century and vast changes in agricultural practices in the early 20^{th} century not only increased soil erosion, but also dramatically diminished soil and water quality. These past footprints are still visible in the watershed and many recent studies have suggested parts of this watershed are susceptible to increased non-point source pollutant loadings (Lerch et al., 1995; Kitchen et al., 1997; Donald et al., 1998; Blanchard and Lerch, 2000; Lerch and Blanchard, 2003; Lerch et al., 2008).

In 2005, a multi-scale assessment of past management practices effectiveness was initiated with one of the smallest watersheds selected for the study, the Goodwater Creek Experimental Watershed (GCEW; Figure 7.1) with a 76 km^2 area. The GCEW was established in 1971 to study surface water hydrology and was instrumented with three weirs for stream flow measurements. The GCEW is one of the watersheds in the Salt River Basin that has well documented available data. These data include flow measurements at weirs in the stream, herbicide and nutrient loads sampled at the weirs, weather data, cropping systems, and established management practices (Sadler et al., 2006). All these inputs can be used for developing a holistic watershed development study to evaluate best management practices (BMP) to minimize the detrimental impact of intensive agriculture and agricultural inputs on soil and water quality.

In any watershed, some areas are more critical for production and environmental impact relative to other areas (Maas et al., 1985; Storm et al., 1988; Dickinson et al., 1990; Tripathi et al., 2003). These critical areas may have relatively lower agricultural productivity, higher potential for runoff generation, higher potential for leaching potential, and higher potential for generation of non-point source pollutants (Agnew et al., 2006). Therefore, these areas are called Critical Management Areas (CMAs). Identifying critical areas has been a widely accepted option for not only controlling higher runoff and non-point source pollutants, but also to increase productivity per unit land area (White et al., 2009; Gitau et al., 2004). Once critical areas are identified in the watershed, their associated risks can be controlled with site-specific management using the best and most economical practices available for a particular remediation (Gburek et al., 2002; Norris, 1993).

The other motive for the CEAP project was to validate environmental models used by the USDA-Natural Resources Conservation Service (NRCS) for their national assessment (Richardson et al., 2008). Simulation models are one of the tools used for estimating pollutant loads in a watershed and for delineating CMAs. Srinivasan et al. (2005) compared two models, SWAT (Soil and Water Assessment Tool) and a physically-based model Soil Moisture Distribution and Routing (SMDR) for delineating critical source areas (similar to CMAs) for runoff generation and phosphorus transport. They found these models had the capability for simulating spatial data representing runoff generation at the watershed scale. Busteed et al. (2009) used the SWAT model to target critical source areas generating high amounts of sediment and phosphorus loads in the Wister Lake Basin, Oklahoma. They found just 10% of the basin was generating 85% of the total pollution. Therefore, they were able to target specific agricultural producers to enroll them in their water quality program that optimized limited cost share funds.

Simulation models require large amounts of input parameters; calibration and validation of models are thus an important step for improved simulation of runoff and non-point source pollutants that match monitored outputs (Engel et al., 2007). Therefore, delineating CMAs through model simulation can be complex and tedious. In chapter 5, we showed that correlations between physically measured soil and land properties and areas that generate non-point source pollutants existed at the field level. If extended to the watershed scale, this approach, which is based on soil properties and topography, would minimize the requirement for specific modeling expertise to delineate CMAs and target them for BMPs .

In claypan soils, the depth to claypan is a good indicator of soil quality; this parameter has been found in many studies to impact generation of surface runoff and non-point source pollutants (Chapters 4, 5, and 6; Ghidey et al., 1997; Ghidey et al, 1999) as well as crop yield (Kitchen et al., 2005; Lerch et al., 2005). The study in Chapter 5 successfully delineated CMAs in a 32 ha field containing claypan soils (fine, smectitic, mesic Aeric Vertic Epiaqualfs and Vertic Albaqualfs) using two indices, the Claypan Index (CPI; Equation 1) and the Conductivity Claypan Index (CCI; Equation 2).

$$\boldsymbol{CPI = {}^{CD}/_{SL}} \qquad [1]$$

$$\boldsymbol{CCI = Ksat * {}^{CD}/_{SL}} \qquad [2]$$

where, CD is the depth to the claypan (mm), SL is the average area slope (%), and Ksat is the surface saturated hydraulic conductivity (mm/h). Moderate to strong correlations were found between areas generating higher amounts of runoff, sediment yield, and atrazine loads and the indices calculated for those areas. These areas were also found to have lower corn yields.

Based on these previous results, the hypothesis for the present study was that the indices used at the field scale for delineation of CMAs for claypan soils could also delineate CMAs in the GCEW, which is in the claypan region. The specific objectives of the study were: 1. to delineate CMAs in the GCEW using two indices, CPI and CCI; 2. to validate CMAs by using the simulation model SWAT; and 3. to target placement of CMAs for selected BMPs to reduce runoff, herbicide, and nutrient loads at the watershed outlet.

Methodology

Study Area

The Goodwater Creek Experimental Watershed (GCEW) is located northeast of Columbia, MO and is dominantly an agricultural watershed with total area of 7600 ha (Figure 7.1). The 7200 ha area of the watershed drains at the northern weir (Weir 1), which is nested inside the watershed (Figure 7.2).

The two major soil associations in the GCEW are the Adco-Putnam-Mexico (fine, smectitic mesic Vertic Albaqualfs; fine, smectitic, mesic Vertic Albaqualfs; fine, smectitic, mesic Vertic Epiaqualfs) and the Mexico-Leonard (fine, smectitic, mesic Vertic Epiaqualfs). All these soils have claypans at a depth ranging from 15 to 60 cm. As a result, these soils are predominantly classified in hydrologic groups C and D, the two highest runoff generating soil categories. The land uses in the watershed include agricultural crops and pasture (87%), forest (8%), low residential density urban areas (4%), and small water bodies (~1%). Major agricultural crops are corn (*Zea mays*), soybean (*Glycine max*), wheat (*Triticum aestivum*), and grain sorghum (*Sorghum bicolor*). The tillage management in the watershed is dominantly conventional, conservation, and no-till (Ghidey et al., 2005; Sadler et al., 2006). The average annual rainfall in the watershed is 968 mm, and average daily maximum and minimum temperatures are 16.9 and 6.3 °C, respectively, based on the weather station measured data from 1978 to 2007 installed inside the watershed.

Data Collection

The topography data for GCEW were acquired from processing the elevation data downloaded from USGS site (U. S. Geological Survey; http://seamless.usgs.gov/) to a Digital Elevation Model (DEM) of 10-m resolution. Soil data were obtained from USDA-Natural Resources Conservation Service, Soil Survey Geographic Database (SSURGO; http://datagateway.nrcs.usda.gov/Gatewayhome.html.). The land use data for 2005 were collected from the Missouri Spatial Data Information Service (MSDIS; www.msdis.missouri.edu) and were classified into five different classes including agriculture, forest, pasture, urban, and water bodies. The agricultural cropland was further divided into four different crops, based on the 10-year average (1995 – 2005) collected from the National Agricultural Statistics Service (NASS; http://www.nass.usda.gov); cropland consisted of 49% soybean, 35% corn, 10% wheat, and 6% grain sorghum. Corn and soybean fields were further divided into different tillage systems based on the data from 1995 to 2005 downloaded from the Conservation Technology Information Center

(CTIC; www.ctic.purdue.edu). Corn crop was divided into three tillage systems: conventional (25.7%), conservation (62.9%), and no-till (11.4%); soybean crop was divided into two different tillage systems conservation (20.4%), and no-till (79.6%), whereas all of the wheat and grain sorghum was kept under no-till and conventional tillage systems, respectively.

Weather, Runoff, Atrazine, and Nutrient Data

The long-term hydrologic database details for the GCEW were documented by Sadler et al. (2006). Figure 7.2 shows the network of rainfall and weather station locations used for the present simulation study. The weather station was installed and started in 1991 and was fully functional in 1993. From this station, sub-daily rainfall (mm), temperature ($^{\circ}$C), average solar radiation (MJ m^{-2}), relative humidity (fraction), and wind speed (mm h^{-1}) data were collected, recorded and maintained in a server database managed by the USDA-ARS Cropping Systems & Water Quality Research Unit (CSWQRU) at the University of Missouri (Sadler et al., 2006). Similarly, rainfall data from the other five rainfall gauges are maintained and are available from 1971 to present.

Three pre-calibrated broad crested 10:1 V-notch weirs were installed in the watershed in 1971 (Figure 7.2) and sub-daily flow data were recorded by using stage recorders and a rating curve for each weir. The data for Weir 1 at the northern part of the watershed (Figure 7.2) were used for primary calibration and validation of this model. The flow from the weir was sampled for sediments, nutrients, and pesticides using a combination of auto- and weekly grab samples. Daily transport of these constituents was calculated using these measured concentrations as well as interpolated values on days without measured data. The samples were analyzed for dissolved nitrates [(NO_3 + NO_2)-

N], ammonia (NH_4-N), and phosphates (PO_4-P). For herbicides, atrazine was selected for the present simulation study as it is a common herbicide used by all corn and sorghum producers in the watershed (Murphy et al., 2008).

Simulation Modeling

The simulation model Soil and Water Assessment Tool (SWAT) was used in the present simulation study for simulating runoff, sediment yield, atrazine, and nutrient loadings in the GCEW. SWAT is a continuous daily time step model for river basins or watershed scales developed by the USDA-ARS (Gassman et al., 2007; Neitsch et al., 2002a). SWAT was developed to predict the impact of land management practices on non-point source pollutant transport in larger scale watersheds with diverse soils, land use and management conditions over long periods of time (Neitsch et al., 2002b). Gassman et al. (2007) have provided an extensive review of studies done with the SWAT model. It has been extensively used at watershed or basin scales for simulating total maximum daily loads (TMDLs), to assess the impact of various conservation practices for CEAP (Conservation Effects Assessment Project), and various other soil and water quality research projects (Gassman et al., 2007; Parajuli et al., 2008; White et al., 2009; Cho et al., 2010).

A watershed in SWAT is delineated based on the area draining into the watershed outlet and further subdivided into a number of sub-watersheds known as sub-basins based upon the number of outlets in the tributaries and their drainage area. Each sub-basin is further divided into spatial units known as hydrologic response units (HRUs), unique combinations of land use, soil type and topography. SWAT simulates seven major processes: hydrology, erosion/sedimentation, soil temperature, plant growth, nutrient cycle, pesticide fate and transport, and land management operations (Neitsch et al., 2002a). If unknown, daily weather can be simulated using monthly climatic statistics.

Surface runoff, evapotranspiration, percolation, and return flow are part of the hydrologic component of SWAT that simulates the water balance of the watershed on a daily basis. Surface runoff is estimated using the Natural Resources Conservation Service (NRCS) curve number technique (U.S. Department of Agriculture-NRCS, 2004) and is routed through the channel network using the variable storage routing method or Muskingum routing method and the later one was selected for the present study. Potential evapotranspiration was estimated using the Penman-Monteith equation out of three other options based on its performance during calibration. The soil water percolation equations were modified to better handle the restrictive claypan layer (Baffaut, USDA-ARS, hydrologist, personal communication, December 2009). In short, when the soil water content exceeds soil field capacity, soil water percolation from one soil layer to another is calculated by using a storage routing method. Subsurface lateral flow is calculated using a flow kinematic approximation (Sloan and Moore, 1984; Neitsch et al, 2005). In this modification of the code, percolation from one layer to the next is limited by the most restrictive hydraulic conductivity and by the saturation level of the receiving layer. Hydraulic conductivities are also adjusted as a function of soil water content. Finally, any water in excess of the saturation capacity and that cannot percolate or flow laterally is redirected toward the surface layer.

Soil erosion is calculated by the Modified Soil Loss Equation (MUSLE) (Williams, 1975). The major difference between MUSLE and the Universal Soil Loss Equation (USLE) is that MUSLE replaces the rainfall factor with a runoff factor. The

MUSLE is solved for each HRU and final sediment yields are routed down the main channels using a stream power equation. Two processes of soil erosion are simulated in SWAT, one by surface soil erosion in the HRUs and the other in the channel degradation/deposition. Adjustments could be made to the P (management practice) factor of the MUSLE to calibrate sediment yield generated from surface soil erosion. The channel degradation/deposition is dependent on peak channel velocity (Arnold et al., 1995). Two parameters can be adjusted for calibration of channel erosion: the linear parameter (SPCON) and the exponential (SPEXP) parameter of the sediment routing equation.

The nutrient and pesticide movement in the soil and streams is adapted from the model GLEAMS (Groundwater Loading Effects of Agricultural Management Systems; Leonard et al., 1987) and EPIC (Erosion-Productivity Impact Calculator; Williams, 1995). The details of these processes are provided by Neistch et al. (2002a).

SWAT Model Setup

The latest version of the model SWAT with an ArcInfo user interface (ArcSWAT 2009.93.3) was used for the present simulation study. Based on the 10 m DEM and using auto delineation in ArcSWAT, the watershed boundary was created and was divided into eight subbasins (Figure 7.2). The watershed was also divided into four different slope classes 0 – 0.5%, 0.5 – 1.0%, 1.0 – 3.0%, and >3.0% based on the 10 m DEM. The SSURGO soil map, land use map and slope map of the watershed were overlaid and resulted in HRUs (hydrologic response units). The percentage area in each subbasin for different soil series, land use, and slope classes is provided in Table 7.1.

Based on studies done in the claypan region for estimating and comparing soil hydraulic properties for different land uses (Chapter 3; Rachman et al., 2004; Seobi et al., 2005; Udawatta et al., 2008), the depth to claypan, and surface Ksat of each soil series were adjusted depending upon the land use and slope class (Table 7.2). The NRCS soils database for each soil series was used as a benchmark for the surface Ksat values. Based on the field and laboratory studies for estimating soil hydraulic properties in claypan soils, the shallowest depths to claypan and lowest values of Ksat were assigned on the steepest slopes and for agricultural and urban land use. In contrast, the soils on gentle slope classes and for forest or pasture land use had the deepest depth to claypan and the highest Ksat values. The Ksat values were always kept within the range provided in the NRCS soils database.

Crop management operations such as planting, fertilizer and herbicide applications, tillage, and harvesting were scheduled based on heat units; the model estimates the total heat units accumulated every day until the end of a year and applies an operation on the day when the heat unit specified for the operation equals the number of heat units accumulated (Neitsch et al., 2002a). The management scenarios for corn, soybean, and wheat are provided in Tables 7.3 and 7.4 for conventional and no-till management. The conservation tillage management was the same as the conventional tillage system except that a chisel plow was used instead of a moldboard plow. The planting dates in the watershed were adjusted spatially as well as temporally based on the planting progress reports for the simulation period (NASS, 2010). This was done by using a subprogram added to the model SWAT by Dr. Claire Baffaut (personal communication; CSWQRU, USDA-ARS, Columbia, MO). This subprogram relies on management operations being based on heat units. When a planting operation is scheduled to take place, the program compares simulated planted acres in the watershed to the planting progress record in that year and only performs the planting operation if additional acres need to be planted to match that record. Thus it allows different HRU having the same management to be planted on different dates based on the NASS data. The date of any operation that is scheduled between planting and harvesting is then a function the heat units accumulated since planting.

In the 2009 version of the SWAT model and associated interface ArcSWAT 2009.93.3, the simulation of best management practices (BMPs) like grassed waterways (GWW), filter strips (FS), terraces, forest buffers, and sediment dikes have been added. The present study uses the simulation capability of this model's version for simulating GWW, FS, and terraces, which are explained briefly. Since these BMPs were assigned to a series of HRU in the watershed, default values were used whenever possible so that the size of the BMP would be a function of the HRU area.

Any combination of BMPs can be specified for selected HRUs and their starting year can be specified for any time during the simulation period. The terrace simulation requires specifying the desired average slope length between terraces, which determines the number and width of terraces, the curve number of the terraced field and the USLE practice factor (P). These parameters are the basis for the reductions in runoff and soil loss. Simulation of FS requires the ratio of the HRU area to the FS area and the recommended values are 40 to 60. The other two parameters are used to calculate the efficiency of the filter strip. The parameter VFSCON sets up the fraction of the total runoff from the entire field entering the most concentrated 10% of the FS, the recommended value is 0.5, the other factor VFSCH estimates the amount of flow transported through the FS in the channel, and its recommended value is zero unless FS has failed. SWAT simulates the GWW as a trapezoidal vegetated channel with a side slope of 8:1. When not specified, the length of GWW is assumed to be equal to one side of the HRU, i.e., the square root of the HRU area; its slope is assumed to be three quarters of the HRU slope. A linear parameter and Manning's n are used for controlling sediment entrained and the reduction in flow velocity. The water level in GWW is estimated depending on the total runoff coming from the HRU. The surface area of GWW above the water level is simulated as a filter strip for runoff and dissolved pollutants infiltration and trapping of suspended sediments and associated pollutants.

Calibration and Validation of SWAT

The model was calibrated from 1993 to 2000 and validated from 2001 to 2008 at a monthly time step for stream flow, sediment yield, atrazine load, dissolved nitrate, and dissolved phosphorus at Weir 1 (Figure 7.2). The model's goodness of fit was evaluated with the coefficient of determination (r^2), the Nash and Sutcliffe (1970) efficiency (NSE), and the percent bias (Pbias). These criteria have been extensively used in modeling studies (Ramanarayanan et al., 1997; Santhi et al., 2001; Wang et al., 2007), and are explained in detail by Krause et al. (2005) and Moriasi et al. (2007). Many researchers have considered various acceptable ranges for r^2, NSE and Pbias based upon the amount of available measured data, output time interval, and purpose of the study. Moriasi et al. (2007) provided acceptable ranges for NSE and Pbias when quantifying the accuracy of monthly simulations of watershed runoff and pollutant loadings. The acceptable values in the present study for calibration and validation follow the recommendations from Moriasi et al. (2007): r^2 and NSE greater than 0.5; Pbias values were different depending on the model output: for stream flow the selected range was -25% < Pbias < 25%, and for sediment yield, atrazine load, and dissolved nitrogen and phosphorous, it was -55% < Pbias < 55%.

The major parameters considered for calibration and validation were based on prior studies done in the GCEW using the SWAT model (Ghidey et al., 2005; Bockhold et al., 2006; Ghidey et al., 2006). All the major parameters adjusted for the presented study during calibration are shown in table 7.5 with the respective adjusted values. A detailed discussion on all the SWAT parameters is given in Neitsch et al., (2002a).The stream flow was calibrated first, followed by sediment yield, atrazine load, and then nitrogen and phosphorus loads. The parameters considered for flow calibration were divided into four different classes. The first is the water balance parameters which include snow melt temperature (SMFMX and SMFMN) and snow cover parameters (SNOCOVMX and SNO50COV), evapotranspiration equation, soil evaporation compensation factor (ESCO), and plant uptake compensation factor (EPCO). The second is surface runoff parameters which include the SCS curve number (CN), and surface lag (days) in subbasins large enough to have time of concentration more than one day (Neitsch et al., 2002a). The third concerns the groundwater components. Other than specifying the initial depth of shallow and deep aquifers, the major groundwater parameters were ground water delay (GW_DELAY) in days, and ALPHA_BF (days) that are directly related to the groundwater flow response to changes in recharge. Groundwater can also move upwards into the overlying unsaturated soil zone to meet the evapotranspiration demand, in amounts controlled by the revap coefficient

(GW_REVAP). The fourth is the reach routing component. In the SWAT simulation studies done before for GCEW the Muskingum routing equation was used (Ghidey et al., 2005), and the model was found to be sensitive to the two routing calibration coefficients that are used to control the impact of storage time during normal and low flow. Other than these coefficients, Manning's roughness coefficient for the channel (*n*) also impacts the flow velocity during the routing (Neistch et. al., 2002a).

Pesticide fate and transport are dependent upon two types of parameters. One set is pesticide specific and includes the degradation half-life of the chemical in the soil (HLIFE_S), the degradation half-life of the chemical on the foliage (HLIFE_F), and the soil adsorption coefficient (SKOC) for the pesticide. The soil adsorption coefficient is the ratio between the pesticide concentration in the soil to the pesticide concentration in the solution. It is highly dependent on the soil organic carbon content. The other set of parameters controls the amount of pesticide transported via surface runoff or groundwater; these are the wash-off fraction (WOF) and pesticide percolation coefficient (PERCOP).

The calibration of nutrient concentrations is dependent upon many processes, especially nitrogen because of its capacity to vary its valance state. Nitrogen becomes more mobile in different environmental conditions (Neitsch et al., 2002a). SWAT simulates nitrogen by maintaining five different pools: organic nitrogen is found in active, stable and fresh nitrogen pools and inorganic nitrogen, which can be in ammonia (NH_4^+) or nitrate and nitrite (NO_3^-, NO_2^-) forms. Major parameters that control the conversion of nitrogen into different pools were adjusted during calibration. These included the mineralization rate of the humus active organic nitrogen (CMN), the mineralization rate of the residue fresh organic nitrogen (RSDCO), the denitrification rate (CDN) and the threshold value of nutrient cycling water factor for denitrification to occur (SDNCO). Similarly for phosphorus (P), SWAT maintains two components: organic and inorganic P. Two main parameters can be adjusted during calibration. These include the phosphorus soil partitioning coefficient (PHOSKD), and the phosphorus availability index (PSP).The leaching component for both nutrients is also an important parameter; nitrate leaching is controlled by NPERCO and phosphorus leaching by PPERCO.

Delineation of Critical Management Areas (CMAs)

Two sets of CMAs were delineated based on the CPI (Equation 1) and CCI (Equation 2) indices. These were only applied to the land under agricultural crops not including pasture because these indices were developed only for agricultural fields during study in chapter 5. The three parameters that were used as inputs to the SWAT model and needed for index calculations were surface Ksat, depth to the claypan, and average slope. Using these three input parameters, the indices were calculated for all of the HRUs under agricultural land use. Once the CCI and CPI values for all agricultural HRUs were calculated, they were correlated with different output parameters simulated by the model SWAT. The correlations between model outputs and indices were evaluated by calculating the coefficients of correlation (*r*) between each index and the 16 year (1993 to 2008) annual average selected model outputs for all of the HRUs under agricultural land use. The significance of *r* values was estimated by using t-statistics with n-2 degrees of freedom at 95% confidence level (Kaps and Lamberson, 2007). The n value would be dependent upon the number of HRUs to be delineated as CMAs

The index with highest *r* values was selected for delineation of CMAs in the watershed. The study in Chapter 5 found the indices were negatively correlated with CMAs; therefore the HRUs under agricultural land use covering 25% of the total watershed with the lowest values of indices were treated as CMAs. Then to ascertain the validity of CMAs delineated by the indices, the agricultural HRUs covering 25% of the total watershed area found to have highest sediment yields simulated by SWAT were also treated as CMAs and were called CMAs delineated using the model based technique.

Scenario Analysis for Selected BMPs

After the delineation of CMAs, these areas were put into three different BMPs: filter strips (FS), grassed waterways (GWW), and terraces. GWW and terraces were the most common current practices in the GCEW and there is evidence that filter strips could be beneficial to decrease off-site transport of dissolved compounds such as herbicides and dissolved nutrients (Lin et al., 2007, 2008). The distribution of BMPs among the CMAs was done in two different ways. In the first one, the current percentage of each individual BMPs out of all BMPs installed in the GCEW was estimated and the three selected BMPs (FS, GWW, and terraces) were distributed among the CMAs with similar percentages, these percentages were FS on 3%, terraces on 16% and GWW on 81% of total area that were put under CMAs. In the second one, all the CMAs with slopes greater than 3% were put under terraces with the rest of the CMAs divided randomly into two parts, one part was put under FS and the other under GWW. In order to compare the reductions in runoff, sediment yield, atrazine loads, and nutrient loads at the watershed outlet, a base scenario was first developed, i.e. without any BMPs. Then putting BMPs on CMAs delineated by index based technique and model based technique separately. All the above combinations gave rise to five different scenarios and are described in Table 7.6.

The calibrated and validated SWAT model was run for these five scenarios for 30 years, from1979 to 2008. Measured rainfall and temperature data were used, whereas radiation, relative humidity, wind speed and potential evapo-transpiration were simulated from 1979 to 1990 by the model. After 1990, all necessary weather variables were measured. The crop management operations were left unchanged from the calibrated model for all of the scenarios. The BMP scenarios were evaluated using annual average values. Statistical analysis was performed using a t-test with the PROC GLM procedure (SAS Institute, 1999) at the 90 % significance level to test differences between annual average simulated runoff, sediment yield, atrazine loads, nitrate loads and phosphorus loads for the five scenarios. Since data were not normally distributed, a log transform was conducted to normalize the data. Before the statistical comparison all the model output values were log normalized.

Results

Calibration and Validation

The results of calibration and validation of the SWAT model for streamflow, sediment yield, nutrient loads, and herbicide load are presented in Table 7.7. Streamflow had very good calibration and validation efficiency values, the scatter graphs between measured and simulated results are shown in Figure 7.3. Ghidey et al. (2007) in a separate simulation study using model SWAT for GCEW and using SSURGO soil data for streamflow found r^2 and NSE values for calibration and validation on a monthly time scale as 0.76 and 0.72, and 0.67 and 0.66, respectively, in comparison to the r^2 and NSE values for calibration and validation of 0.85 and 0.83, and 0.89 and 0.78, respectively, for the present study. The improvement in efficiency values could be attributed to better representation of depth to the claypan and surface Ksat value for various land use and slope classes and improvement in the SWAT model. In addition, the number of years during calibration was eight years in comparison to five years (1993 to 1997) in the previous study.

The various parameters that were discussed in the methodology section were adjusted and their values used during calibration are presented in Table 7.5. The curve numbers and surface lag time in days for runoff were found to have maximum impact on the streamflow. Curve numbers were adjusted based on land use, using a minimum for forest (78) and a maximum for urban land (89); the surface lag value of 5.5 days was found to be best. Other than these factors, the snow melt parameters (SMFMX: Melt factor for snow on June 21 and SMFMN: Melt factor for snow on December 21 [mm H2O/ºC-day]) were adjusted. Their limits were a little higher than specified for rural watersheds and lower than specified for urban watersheds as discussed in the methodology section.

The sediment yield was calibrated and validated satisfactorily (Figure 7.4) and was marginally over predicted during calibration (Pbias = -17.4%), and under during the validation (Pbias = 15.0%). The P factor is dependent on HRU management and was adjusted with its lower limit kept in the low range (Table 7.5). Since approximately 14% of the watershed was placed under three different BMPs after 1990 (filter strips, grass waterways, terraces) which were not simulated in the model, using low values for P would be acceptable and the reason for using these values.

Calibration of atrazine has been attempted before with the SWAT model for the same watershed by Bockhold et al. (2006); they found the simulated atrazine load and measured values did not match well because of insufficient accuracy in the atrazine application dates in the watershed. In the present study, management was scheduled based on heat unit values, which provided good calibration efficiency values (Figure 7.4). However during the validation period, the r^2 and NSE values for atrazine loads were both below satisfactory levels. During validation, the Pbias was only -5.8%, therefore the net amount of atrazine load coming out at Weir 1 was in good agreement with measured values but the peak values were occurring in different months. This can again be attributed to insufficient accuracy for atrazine application dates. The parameters adjusted for atrazine during calibration are shown in Table 7.5.

Achieving good agreement between measured and simulated values for nutrients was very challenging, due to a couple of reasons. Nitrogen is highly mobile in soil and water (Neitsch et al., 2002a), and furthermore, application dates for fertilizers were not available at the watershed level. Ghidey et al. (1999) and Lerch et al. (2005) in two separate studies have concluded that the maximum amount of nutrient loss occurs if there is a runoff event just after the application of fertilizers in claypan soils. This challenge also increases the probability of additional fertilizer applications after these events. The calibration of nitrate loads was not found to be satisfactory; these loads were always over predicted especially during the validation period (Figure 7.5). Even though the rate of denitrification was increased, the rate of organic nitrogen conversion to nitrate was reduced and the percolation rate of nitrate was increased from 0.2 to 0.3, the model over predicted nitrate loads.

Simulation of phosphorus loads had satisfactory efficiency values during both the calibration and validation periods (Figure 7.5). Slight changes in default parameters values were able to attain good agreement between measured and simulated phosphorus loads. The PSP parameter was changed from 0.4 to 0.5, the PHOSKD parameter was changed from 175 to 185, and the percolation coefficient (PPERCO) was changed from 10 to 11 (Table 7.5).

Delineation of Critical Management Areas (CMAs)

At the field scale these indices were successful in delineating areas generating higher amounts of runoff, sediment yield, and atrazine load. The poor simulation results for nutrients on field 1 limited our ability to test whether these indices would be also successful in delineating areas generating higher amounts of nitrogen and phosphorus. Thus, at the watershed scale, the primary objective of these indices was to delineate CMAs that were generating high runoff, sediment yield and atrazine loads. The correlations between the CCI and CPI index values calculated for HRUs under agricultural land use other than pasture are shown in Tables 7.8 and 7.9 along with their respective model outputs.

The highest correlations were found between areas generating higher amounts of sediment yield and both the index values. On the other hand, *r* values were moderate between runoff and index values. There was no correlation between atrazine loads and index values. Therefore at the watershed scale, these indices were able to delineate areas with high amounts of sediment yield and surface runoff, but not atrazine loads as was found in the field study (Chapter 5).

These indexes were also correlated with other model outputs, as shown in Tables 7.8 and 7.9. The lateral flow and nitrate in lateral flow had good correlations with the indices; however, the amount of lateral flow was found to be very low in comparison to the surface runoff in the GCEW, therefore this model output could not be indicative of CMAs.

Observations of the data indicated that some areas of the watershed were excessively critical and generated a much higher proportion of pollutants, which were correlated well with the index, than the rest of the watershed. CMAs delineated by index based technique were generating 50, 57, 24, and 22% of sediment load, organic phosphorus, runoff, and atrazine load of the total amount generated by agricultural land in the watershed. Similarly by model based technique CMAs were generating 72, 74, 33, and 24% of sediment load, organic phosphorus, runoff, and atrazine load in comparison to the total generated by the agricultural land in the watershed.

Out of the total area delineated as CMAs by both indices 1700 ha area matched. The 300 ha area that was not delineated by CPI was the lowest sediment yielding area among the CMAs delineated by CCI, on the other hand the 300 ha area that was not delineated by CCI was also the moderately runoff generating area among CMAs delineated by CPI. The index CCI had slightly better correlation for runoff in comparison to CPI; but the rest of the model outputs had similar *r* values for both indices. Therefore, in order to also cover the areas that had better correlation with runoff, the CMAs delineated by using the CCI index were treated as CMAs in the GCEW watershed.

The model CMAs captured 70% of CMAs that were delineated by the CCI index, and they were homogenously divided among the subbasins. The spatial distribution of

CMAs within each subbasin is shown in Table 7.10. CMAs delineated with the CCI index and with the model results are considered. The upstream area of the watershed had a higher percentage of CMAs. The most upstream four subbasins (1, 2, 3, and 4; Figure 7.2) constituted 45% of the total watershed area and had 60% of the CMAs by area. CMAs were dependent upon soil type and slope, the Mexico soil with a slope class of 1 to 3% covered 88.2% of CMAs by area, whereas Leonard and Armstrong series with slopes greater than 3% covered 9.2 and 2.6% of the CMAs by area, respectively.

The correlation between CMAs and crop yields were not found to be satisfactory and expected. The SWAT model also simulates the number of days the crop remains under water or nutrient stresses, so to evaluate the impact of the CCI index on these stresses the *r* values were calculated between water, nitrogen and phosphorus stresses for all of the crops (Table 7.8). The water and nitrogen stresses were strongly and significantly correlated with the CCI index, and the phosphorus stress was moderately but significantly correlated.

The CCI index used for CMA delineation was significantly correlated with many simulated outputs which suggest these CMA areas were susceptible to runoff and generation of non-point source pollutants. The index was not highly correlated with crop yields, but these CMAs were found to have higher water and nutrient stresses for all of the crops except soybeans (Table 7.8).

Scenario Analysis for Selected BMPs

Five scenarios using different BMPs were run with the calibrated/validated SWAT model. Only model outputs for which calibration and validation results were satisfactory were considered: streamflow, sediment yield, and phosphorus load. In addition, the atrazine load was also included in the BMP scenario analysis because, even though calibration/validation showed poor distributions of monthly peaks as suggested by weak r^2 and NSE values, the total amount of simulated load was close to the measured load as suggested by strong values of Pbias during both periods.

The model outputs for all scenarios are given in Table 7.11. Significant differences were found in sediment yield and phosphorus load for BMPs as compared to the baseline. The four simulations with BMPs lowered the sediment yield and phosphorus loads. The annual sediment yield and phosphorus load variations for all scenarios are shown in Figure 7.6. The differences in streamflow among the simulations were so low these differences could be attributed to mathematical approximations made during simulation modeling. The maximum reduction in phosphorus loading and sediment yield was found with Scenarios 2a and 2b, when the selected BMPs were distributed according to the current distribution of BMPs in the watershed. However, there were no significant differences in average annual or in annual loads between each of the BMP scenarios. The phosphorus load reduction was not significantly different from the baseline with Scenario 3a. The simulated atrazine loads from the four scenarios with BMPs, although numerically lower, were not significantly lower than the baseline simulation.

Discussion

CMAs and Model Output

Many processes and factors impact water quality and land productivity in the watershed that are dependent on soil type, slope, management, weather, etc. Similarly when model outputs and their relationships with the index were further evaluated based on slope, crop type and soils different trends were obtained.

The CCI values for Armstrong soils had the best correlation with surface runoff generated from HRUs for all crops and slopes; the *r* values ranged from -0.64 for corn to the -0.95 for soybeans. The Leonard soil series had the opposite trends with CCI index values and surface runoff, i.e. an increase in CCI values corresponded to an increase in surface runoff, not commonly observed during the present study nor the study in Chapter 5. This could be due to the fact that more amount of water was coming out as lateral flow instead of surface flow for lower CCI values area (areas with higher slope) and it was found the lateral flow from HRUs with the Leonard soil was highest in comparison to other soils and was highly correlated with CCI values; *r* values ranged between -0.82 to -0.87. For other soils and slope classes, surface runoff was not well correlated with the index; however lateral flow was better correlated with the index, this could be attributed to the fact that the lateral flow estimated by the SWAT model is directly proportional to the slope and Ksat and these were the two parameters used to calculate the index CCI. The index was able to capture CMAs generating higher amounts of flow independently of the generation process: surface runoff or lateral flow, although the generation of higher lateral flows with increasing slopes lowered the *r* between surface runoff and CCI.

Sediment yield had a strong and significant correlation with CCI for all soils, slope classes, and crops ($r < -0.84$), except for the corn crop that was moderately correlated ($r = -0.49$) but significant. The corn crop was under three different tillage management systems: conventional, conservation, and no-till. When the *r* value was estimated separately for each tillage management under corn, they ranged between -0.84 to -0.85. The conventional tillage management had the highest annual average sediment yield and was approximately 15 times greater compared to no-till and five times more than conservation tillage. These variations in soil erosion because of the tillage are documented in the literature (Zobeck and Onstad, 1986; Carter, 1994; Rhoton, 2000). Therefore when *r* values were estimated for all three tillage management systems together, there was considerable variation in sediment yield for one CCI value which lowered the overall *r* value for corn. This effect of tillage management was not visible in any other crop because soybean had two tillage management systems, no-till and conservation. Soybean did not have considerable variation in sediment yield. Similarly, wheat and grain sorghum each had only one tillage management each. It can be concluded the CCI effectively delineated areas that were generating higher sediment yields in the GCEW.

Nutrients sorbed on soil also had a strong and significant correlation with the CCI index for all soils, slope classes, and crops (Table 7.8). For the corn crop when *r* values were calculated separately for each tillage management, the *r* values were always lower than -0.80, for organic (sorbed) nitrogen and phosphorus. Even sorbed atrazine load was moderately but significantly correlated with CCI values when these relationships were evaluated by tillage management. The *r* values ranged between -0.35 to -0.39 but soluble atrazine load was very poorly correlated with the CCI index (Table 7.8). These findings were directly related to the better correlation of sediment yield and CCI, as these chemicals were sorbed to soil particles therefore with higher sediment transportation there was also higher transportation of sorbed chemicals.

It was anticipated that CMAs would have lower crop yields than the rest of the watershed i.e. the crop yields should be positively correlated with CCI values as areas with lower CCI values were treated as CMAs. The wheat and grain sorghum crop yields were found to be negatively correlated with the CCI index (Table 7.8). However, corn and soybean yields were not well correlated with the index as was found for field 1 in Chapter 5 but they were positively correlated. Corn and sorghum are more sensitive to water stress than soybean, thus we would have expected corn yields to be correlated with CCI, as is sorghum. However, a more detailed look at the results by soil series can highlight differences in the soils on which these crops are grown.

Crop yield was found to be dependent on soil type and average slopes. On soils located on flatter slopes (Adco and Putnam), all crop yields were negatively correlated with CCI, whereas on soils with steeper slopes (Mexico, Leonard, and Armstrong) wheat was always positively correlated but sorghum and corn were positively correlated only with the Mexico soils. The variation in crop yield could be more attributed to the variation in weather. Kitchen et al. (2005) in a field study on claypan soils found that crop yield was highly dependent on the amount of rain. In addition they found that during wet years, corn yield was higher on landscapes with shallow claypan but during dry or average rainfall years, corn yield was higher on landscapes with thicker top soil. Also, the simulation study in Chapter 6 concluded corn yield was more sensitive on poor quality soils or the soils with lower water holding capacity during dry and average rainfall years. Therefore, the collective effect of soil variations and weather cycles on crop yields negated the impact of CCI for the delineation of CMAs that were also sensitive for land productivity.

Results showed that the nutrient and water stresses were significantly correlated with CCI. So while the net crop yields were affected by many factors, including land slope, weather and soil parameters, the CMAs delineated by the CCI index definitely experienced more stress days during the 16 year simulation period (1993 to 2008).

BMP Scenario Analysis

The reductions in selected model outputs because of BMP implementation were not significantly different between each CMA delineation technique. Therefore, the index based technique appeared to perform similar to the model based technique. In the present simulation study, significant reductions were found in sediment yields and phosphorus loads at the watershed outlet in comparison to the baseline scenario except for Scenario 3a (Table 7.11). Sediment reductions were 51 to 54% for all of the scenarios with a maximum reduction in Scenario 2a; phosphorus reductions were 19% to 23% with a maximum reduction in Scenario 2a and a minimum reduction in Scenario 3a. Both scenarios 2a and 3a were on CMAs delineated by model based technique, and one had highest reduction and another had the lowest in comparison to the baseline. This suggests not only the placement of BMPs but also the type of BMP plays an important role in reducing phosphorus loads at watershed outlet. The current simulation results suggest the three BMPs targeted on the CMAs would reduce sediment yield and phosphorus load significantly with slight deviations relative to the distribution of BMPs in the CMAs.

Bracmort et al. (2006) simulated the impacts of GWW, FS, and terraces using the SWAT model. In order to simulate these BMPs, they changed the parameters sensitive to soil loss and runoff in the model to reduce these model outputs; they found similar results to the present study. They found no reductions in runoff volume and streamflow; these results were attributed to the fact the model outputs sediment yield and nutrient load were more sensitive to the altered parameters. There were reductions in sediment yield by 16 to 32% and phosphorus loads by 10 to 24%. The present study used the latest version of ArcSWAT that includes a better representation of BMPs, but this version also did not find any reductions in atrazine load and streamflow. On the other hand, various field and small watershed studies have found significant reductions in sediment yield, runoff, nutrient loads and herbicide loads by using these three BMPs (Young et al., 1980; Cooper et al., 1987; Coyne et al., 1995; Chow et al., 1999; Fiener and Auerswald, 2003; Arora et al., 2010).

Conclusions

The present simulation study was conducted to delineate critical management areas (CMAs) in the Goodwater Creek Experimental Watershed (GCEW). The GCEW is a part of Salt River Basin located in northeastern Missouri. It is characterized by claypan soils that have a high potential for generating surface runoff and non-point source pollutants. Two indices, the CPI (Claypan Index) calculated by dividing the depth to the argillic horizon by the average slope and the CCI (Conductivity Claypan Index) calculated by multiplying CPI by the surface saturated hydraulic conductivity, were used to delineate critical areas. In a previous study (Chapter 5), these indices were found to be negatively correlated with areas generating higher amounts of runoff, sediment yield, and atrazine load. In the current study, 2000 ha (25% of the total watershed) under agricultural land use having the lowest values of CCI and CPI were delineated as CMAs. Both indices captured a similar area with only 300 ha not coinciding.

The calibrated/validated SWAT model from1993 to 2008 was used to simulate streamflow, sediment yields, atrazine loads, nitrate loads and phosphate loads for the GCEW. The model was able to simulate all of these parameters satisfactorily except for nitrate. Atrazine loads were simulated satisfactorily during the calibration period but not during the validation period; the poor calibration and validation of atrazine and nitrate were attributed to insufficient available data for application dates throughout the watershed.

The CMAs delineated by the indices were evaluated by estimating the coefficients of correlation (*r*) between selected model outputs and index values for all of the Hydrologic Response Units (HRUs, areas with homogenous land use, soil type and slope class within a subbasin). Based on the *r* values, both indices were able to delineate CMAs generating higher amounts of surface runoff, sediment yield, and sorbed herbicide and nutrient loads. CMAs were also found to have more days when the crop was under water and nutrient stresses.

Delineated CMAs were placed under three best management practices (BMPs): filter strips (FS), grassed waterways (GWW), and terraces. Reductions in model outputs satisfactorily calibrated were estimated in comparison to the baseline scenario (no BMPs).The scenario analysis results showed significant reductions in sediment yields and phosphorus loads, non-significant numerical reductions in atrazine load, and insignificant changes in streamflow. There were no significant differences found if BMPs were targeted by using model outputs or by using the CCI index. Simulated outputs were also found to be independent of the spatial distribution of BMPs in the CMAs.

The CCI and CPI indices were effectively able to delineate the CMAs in the watershed with claypan soils; however for better estimation of CMAs, the type of management practice also need to be included. Crop yields were also reduced in the CMAs but only for soils with steeper slopes. The simulation of BMPs with the SWAT model still needs to include parameters that would reduce runoff and herbicides losses as suggested by field studies estimating BMP effectiveness. Therefore more efforts are needed for validating simulation of BMPs in the SWAT model with field measured results.

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Tables

Table 7. 1: Percentage area representing different SWAT model inputs in each subbasin.

	Percentage Area								
	Subbasin								Watershed
	1	2	3	4	5	6	7	8	
Percentage Area in Watershed	13.7	7.3	17.0	7.7	11.9	11.5	13.6	14.8	100
(a) Land Use									
Pasture	14.0	11.7	8.4	18.1	13.3	25.3	16.3	14.7	14.5
Forest	11.0	8.8	9.3	10.4	11.9	8.2	3.5	2.6	7.8
Urban	1.3	0.7	1.1	2.0	1.0	2.2	8.7	14.4	4.2
Agriculture*	74.3	83.1	85.3	73.8	74.4	64.9	73.3	72.7	73.5
Corn No-till	2.9	3.3	3.4	3.0	3.0	2.6	2.9	2.9	2.9
Corn Conservation-till	16.4	18.3	18.8	16.2	16.4	14.3	16.2	16.0	16.2
Corn Conventional-till	6.7	7.5	7.7	6.6	6.7	5.8	6.6	6.5	6.6
Grain Sorghum Conventional-till	4.5	5.0	5.1	4.4	4.5	3.9	4.4	4.4	4.4
Soybean No-till	29.0	32.4	33.3	28.8	29.0	25.3	28.6	28.3	28.7
Soybean Conservation-till	7.4	8.3	8.5	7.4	7.4	6.5	7.3	7.3	7.4
Wheat No-till	7.4	8.3	8.5	7.4	7.4	6.5	7.3	7.3	7.4
(b) Soil Series									
Adco	-	-	-	-	-	9.2	17.2	34.6	8.5
Armstrong	2.8	2.1	1.6	9.9	4.0	-	-	-	2.1
Belknap	11.1	11.5	8.1	5.5	10.3	5.2	1.2	-	6.1
Leonard	-	28.7	10.6	2.2	1.5	18.4	-	21.8	9.6
Mexico	74.7	61.9	69.5	75.0	66.6	56.0	67.3	26.0	59.7
Moniteau	-	-	-	-	-	-	-	0.6	0.1
Putnam	12.3		13.1	11.6	18.2	11.9	16.2	21.4	13.7
Twomile	-	-	1.2	-	-	-	-	-	0.2
(c) Percentage Slope									
0.0 – 0.5	31.0	19.6	28.4	24.2	33.0	23.6	39.2	43.6	30.8
0.5 – 1.0	21.0	16.5	23.6	21.8	16.9	6.8	21.2	24.5	19.1
1.0 – 3.0	45.0	51.1	44.8	47.4	41.2	57.5	38.2	32.3	42.7
3.0 <	3.0	16.8	7.4	11.0	9.4	12.7	3.4	4.0	7.4

* Agriculture was further divided into 7 different land uses based on crop and tillage

Table 7. 2: Soil surface saturated hydraulic conductivity (K_{sat}) and depth to claypan (CD) adjusted values based on slope and land use.

Land Use	Percent Slope							
	0 – 0.5		0.5 – 1.0		1.0 – 3.0		>3.0	
	Ksat (mm/h)	Clay depth (mm)	Ksat (mm/h)	Clay depth (mm)	Ksat (mm/h)	Clay depth (mm)	Ksat (mm/h)	Clay depth (mm)
Mexico Soil Series								
Agriculture/ Urban land	10	450	5.5	400	*3.2**	*355*	1.5	200
Forest/ Pasture	25	550	15	500	10	350	5.5	310
Putnam Soil Series								
Agriculture/ Urban land	15	500	9	470	*4.3*	*431*	2	370
Forest/ Pasture	30	600	20	540	15	500	9	460
Adco Soil Series								
Agriculture/ Urban land	15	450	8	400	*4*	*330*	2	250
Forest/ Pasture	20	550	15	500	8	430	4	350
Leonard Soil Series								
Agriculture/ Urban land	15	450	10	350	5	*304*	*2.9*	275
Forest/ Pasture	25	550	20	500	12	320	5	220
Armstrong Soil Series								
Agriculture/ Urban land	12	350	8	300	3	220	*1.2*	*177*
Forest/ Pasture	20	450	15	400	8	320	3	220
Belknap Soil Series								
Agriculture/ Urban land	8	-[$]	5	-	*2.4*	-	1.5	-
Forest/ Pasture	15	-	8	-	5	-	3	-

* The numbers in italics were the original values used by SWAT for specific soil series.
$ There was no claypan found.

Table 7. 3: Crop and tillage management for conventional tillage.

Crop type	Management in Chronological Order
Corn	General Fall Plowing (Moldboard plowing) Anhydrous Ammonia @168 kg ha-1 (injected) Elemental Nitrogen @ 33.6 kg ha-1 Elemental Phosphorous at 39.4 kg ha-1 Disking (Disc Plow Ge23ft) Planting Atrazine (2.25 kg ha-1) Cultivation (Row cultivator Ge 15 ft) Harvest/kill
Soybean	General Fall Plowing (Moldboard plowing) Elemental Nitrogen @ 22.4 kg ha-1 Elemental Phosphorous at 20 kg ha-1 Disking (Disc Plow Ge23ft) Planting Cultivation (Row cultivator Ge 15 ft) Harvest/kill
Wheat	General Fall Plowing (Moldboard plowing) Elemental Nitrogen @ 44.8 kg ha-1 Elemental Phosphorous@ 30 kg ha-1 Disking (Disc Plow Ge23ft) Planting Elemental Nitrogen@ 67.2 kg ha-1 Harvest/kill

Table 7. 4: Crop and tillage management for no-till.

Crop type	Management in Chronological Order
Corn	Anhydrous Ammonia @168 kg ha-1 (knifed)
	Elemental Nitrogen @ 33.6 kg ha-1
	Elemental Phosphorous @ 39.4 kg ha-1
	Atrazine @ 1.25 kg ha-1
	No-till mixing
	Planting
	Atrazine@ 1.25 kg ha-1
	Harvest/kill
Soybean	Elemental Nitrogen @ 22.4 kg ha-1
	Elemental Phosphorous @ 20 kg ha-1
	No-till tillage
	Planting
	Harvest/kill
Wheat	Elemental Nitrogen @ 44.8 kg ha-1
	Elemental Phosphorous @ 30 kg ha-1
	No-till tillage
	Planting
	Elemental Nitrogen@ 67.2 kg ha-1
	Harvest/kill

Table 7. 5: Important SWAT model parameters adjusted during calibration.

Model output variable	Parameter	Adjusted Value
Streamflow	SMFMX: Melt factor for snow on June 21 [mm H2O/ºC-day]	6.0
	SMFMN: Melt factor for snow on December 21 [mm H2O/ºC-day]	1.5
	SNOCOVMX: Minimum snow water content that corresponds to 100% snow cover [mm]	150.0
	SNO50COV: Fraction of snow volume represented by SNOCOVMX that corresponds to 50% snow cover	0.6
	SURLAG: Surface runoff lag time [days]	5.5
	ESCO: soil evaporation compensation factor	0.95
	EPCO: plant water uptake compensation factor	0.85
	Curve numbers were adjusted based on land use and crop management	78 to 89
	GW_DELAY : Groundwater delay [days]	25
	ALPHA_BF : BAseflow alpha factor [days]	0.38
	GW_REVAP : Groundwater "revap" coefficient	0.08
Sediment Yield	SPCON: Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	0.0009
	SPEXP: Exponent parameter for calculating sediment re-entrained in channel sediment routing	1.0
	P: USLE management practice factor was adjusted based on management	0.65 to 0.75
Atrazine	HLIFE_S: Degradation half-life of atrazine in the soil [days]	15
	PERCOP: Pesticide percolation coefficient	0.14
Phosphorus	PHOSKD: Phosphorus soil partitioning coefficient	185.0
	PSP: Phosphorus sorption coefficient	0.5
	PPERCO: Phosphorus percolation coefficient	11.0
Nitrogen	CMN: Rate factor for humus mineralization of active organic nitrogen	0.002
	RSDCO: Residue decomposition coefficient	0.03
	NPERCO: Nitrogen percolation coefficient	0.30
	CDN: Denitrification exponential rate coefficient	1.0

Table 7. 6: Scenarios with Best Management Practices (BMPs).

Scenario	Best Management Practices
1	Base: no BMPs were applied and existing crop management in the watershed was simulated.
2	All the CMAs were put under three different BMPs: filter strips (FS), grassed waterways (GWW), and terraces. Three BMPs were distributed among CMAs similar to the current distribution of BMPs in the watershed.
2a	CMAs delineated by model based technique.
2b	CMAs delineated by Indices based technique.
3	All the CMAs were put under three different BMPs: filter strips (FS), grassed waterways (GWW), and terraces. All the CMAs with average slope greater than 3% were put under terraces. CMAs with slope less than 3% were divided into two equal parts based on the area, and one half received FS and the other half GWW.
3a	CMAs delineated by model based technique.
3b	CMAs delineated by Indices based technique.

Table 7. 7: Monthly calibration and validation coefficients of determination (r^2), Nash-Sutcliffe efficiency values (NSE), and percent bias (Pbias) for runoff, sediment, nutrient and herbicide losses.

Constituent	Calibration (1993 to 2000)			Validation (2001 to 2008)		
	r^2	NSE	Pbias(%)	r^2	NSE	Pbias(%)
Flow	0.85	0.83	8.1	0.89	0.78	17.7
Sediment	0.59	0.44	-17.4	0.57	0.57	15.0
Mineral Nitrogen	0.08	-0.79	-5.9	0.03	-6.45	-87.4
Mineral Phosphorus	0.54	0.43	-6.0	0.46	0.43	-3.1
Atrazine	0.64	0.54	23.0	0.20	-1.09	-5.8

Table 7. 8: Coefficients of correlation (*r*) between CCI (Conductivity Claypan Index) and selected model output parameters estimated for each HRU under different crops.

CCI = Ksat*(CD/SL)				
Model Output Parameters	**Coefficient of Correlation (*r*)**			
	Wheat	**Corn**	**Grain Sorghum**	**Soybean**
Runoff	-0.32*	-0.24	-0.28	-0.30
Lateral flow	-0.57	-0.58	-0.58	-0.57
Sediment Yield	-0.86	-0.48	-0.87	-0.84
Organic Nitrogen	-0.93	-0.50	-0.91	-0.88
Organic Phosphorus	-0.93	-0.53	-0.92	-0.86
Dissolved Phosphorus	-0.91	-0.60	-0.88	-0.86
Nitrogen in Lateral Flow	-0.81	-0.73	-0.75	-0.72
Dissolved Atrazine Load	-	-0.03	-0.02	-
Sorbed Atrazine Load	-	-0.17	-0.16	-
Water Stress	-0.78	-0.69	-0.62	-0.61
Nitrogen Stress	-0.80	-0.75	-0.75	-
Phosphorus Stress	-0.57	-0.59	-0.57	-0.33
Crop Yield	-0.31	0.10	-0.53	-0.06

*Values less than -0.22 for wheat, -0.13 for corn, -0.15 for soybean, and -0.22 for grain sorghum are significantly correlated at the $P < 0.05$ level

Table 7. 9: Coefficients of correlation (*r*) between CPI (Claypan Index) and selected model output parameters estimated for each HRU under different crops.

CPI = (CD/SL)				
Model Output Parameters	**Coefficient of Correlation (*r*)**			
	Wheat	**Corn**	**Grain Sorghum**	**Soybean**
Runoff	-0.28*	-0.20	-0.24	-0.24
Lateral Flow	-0.62	-0.63	-0.65	-0.62
Sediment Yield	-0.88	-0.49	-0.88	-0.86
Organic Nitrogen	-0.93	-0.49	-0.89	-0.85
Organic Phosphorus	-0.93	-0.52	-0.89	-0.83
Dissolved Phosphorus	-0.92	-0.62	-0.90	-0.87
Nitrogen in Lateral Flow	-0.85	-0.78	-0.81	-0.76
Dissolved Atrazine Load	-	-0.02	-0.01	-
Sorbed Atrazine Load	-	-0.15	-0.14	-
Water Stress	-0.76	-0.65	-0.57	-0.57
Nitrogen Stress	-0.80	-0.77	-0.79	-
Phosphorus Stress	-0.62	-0.60	-0.53	-0.36
Crop Yield	-0.25	0.07	-0.47	-0.10

*Values lesser than -0.22 for wheat, -0.13 for corn, -0.15 for soybean, and -0.22 for grain sorghum are significantly correlated at the $P < 0.05$ level

Table 7. 10: Spatial distribution of critical management areas (CMAs) among subbasins.

Subbasin	Area Delineated as CMAs by Index (%)	Area Delineated as CMAs by Model SWAT (%)
1	17.6	15.1
2	11.3	10.5
3	20.1	19.4
4	10.6	9.7
5	12.7	13.4
6	13.8	10.3
7	12.4	10.2
8	1.5	11.4

Table 7. 11: Variation in 30 year annual average selected model outputs for different BMP scenarios.

BMP Scenarios	Description of Scenarios	Streamflow (Mm^3)	Sediment Yield (t)	Phosphorus Load (kg)	Atrazine Load (kg)
1	Base: no BMPs were applied and existing crop management in the watershed was simulated.	24757 (a)*	9601 (a)	5653 (a)	231 (a)
	All the CMAs were put under three different BMPs: filter strips (FS), grassed waterways (GWW), and terraces. Three BMPs were distributed among CMAs similar to the current distribution of BMPs in the watershed.				
2a	CMAs delineated by model based technique.	24757 (a)	4373 (b)	4351 (b)	201 (a)
2b	CMAs delineated by Indices based technique.	25097 (a)	4477 (b)	4382 (b)	219 (a)
	All the CMAs were put under three different BMPs: filter strips (FS), grassed waterways (GWW), and terraces. All the CMAs with average slope greater than 3% were put under terraces. CMAs with slope less than 3% were divided into two equal parts based area, and one half received FS and the other half GWW.				
3a	CMAs delineated by model based technique.	24757 (a)	4665 (b)	4575 (ab)	220(a)
3b	CMAs delineated by Index based technique.	25097 (a)	4515 (b)	4413 (b)	199 (a)

* Values with different letters were found to be significantly different in the same column

Figures

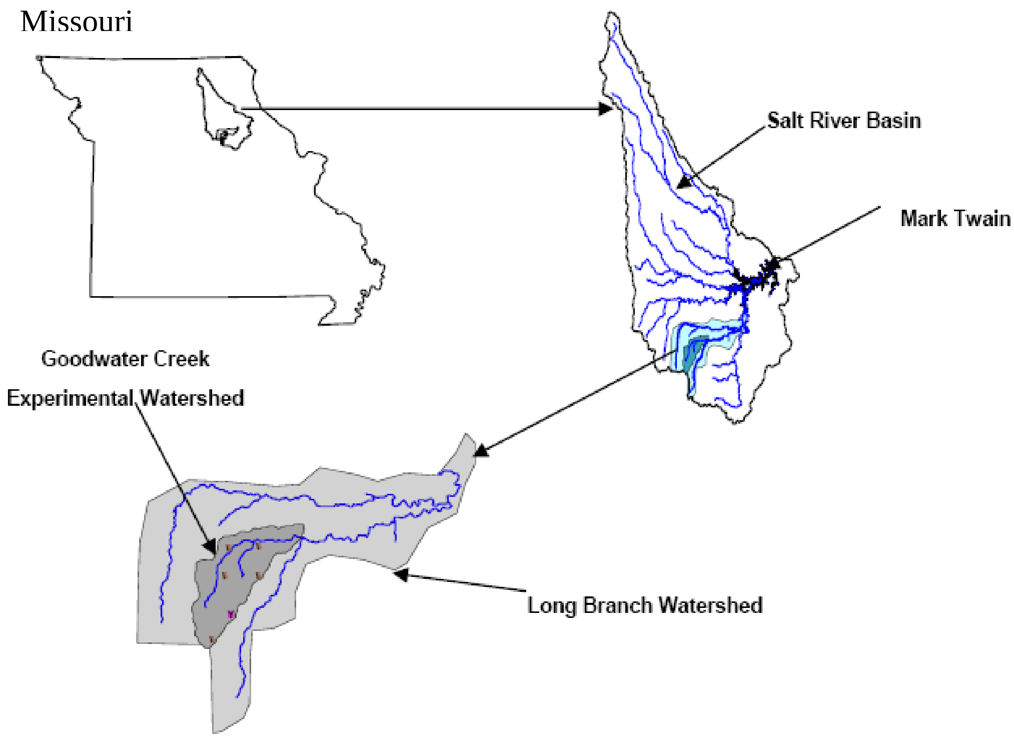


Figure 7. 1: Location of Goodwater Creek Experimental Watershed (GCEW) within the Salt River Basin.

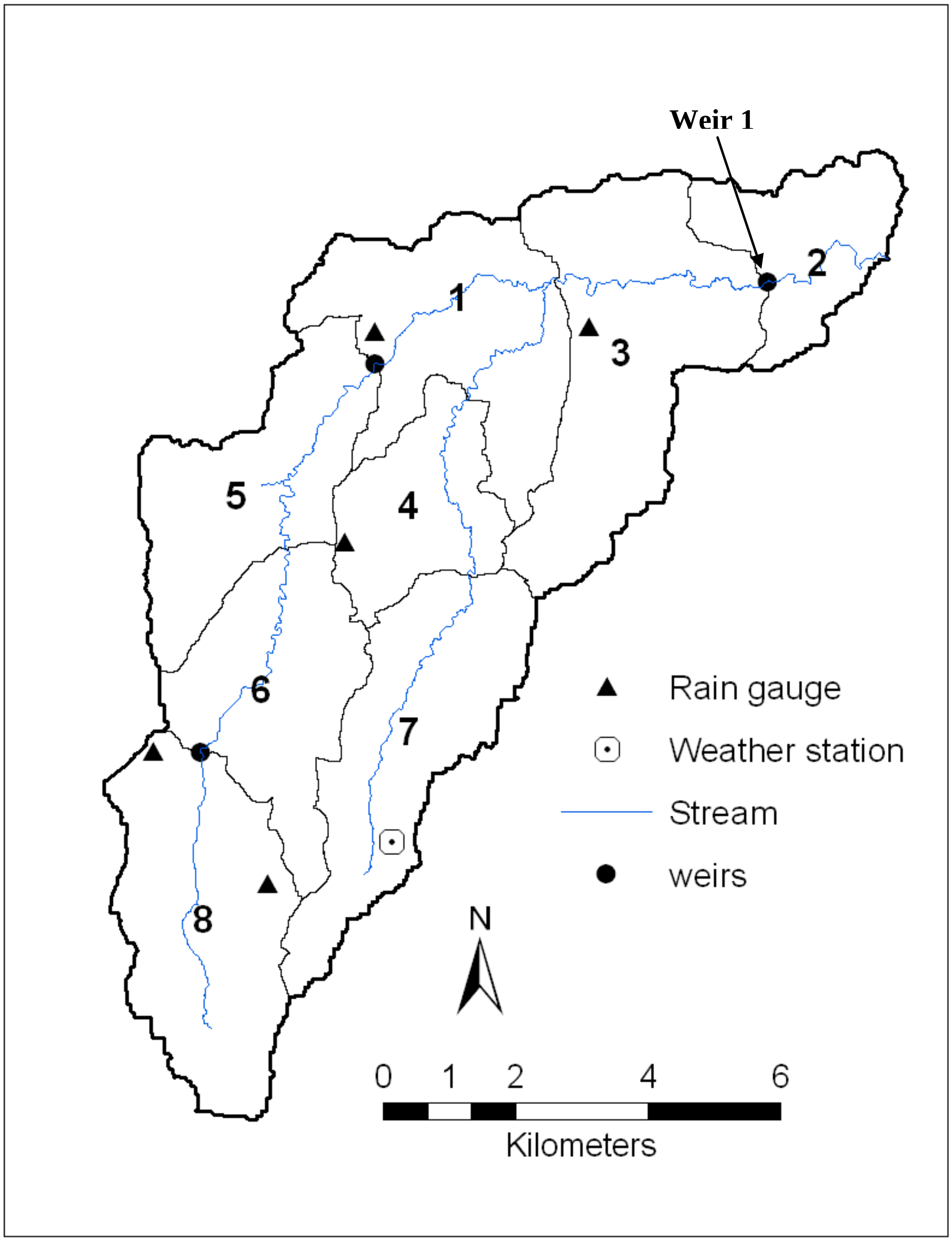
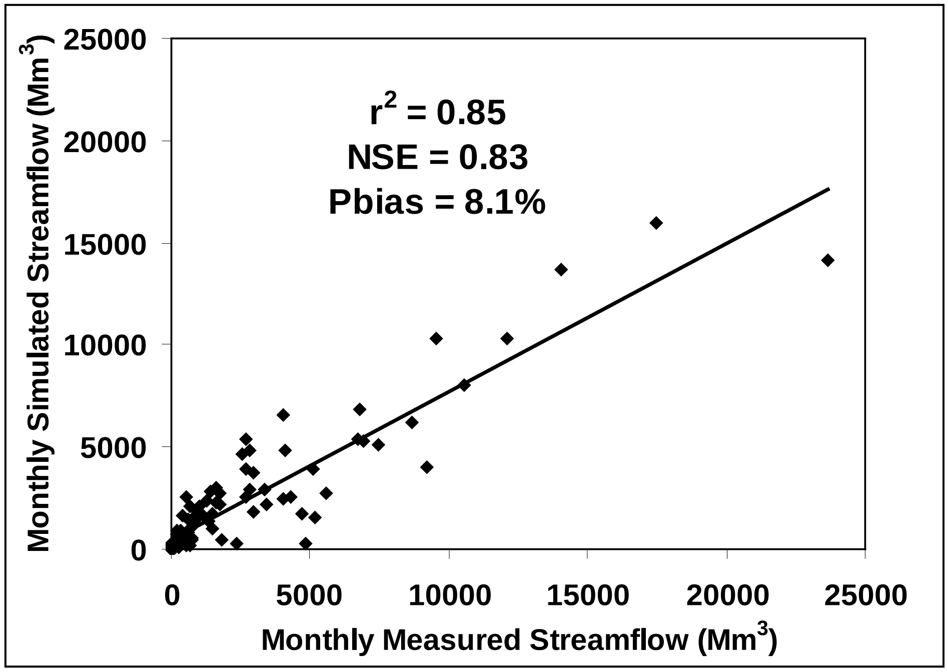
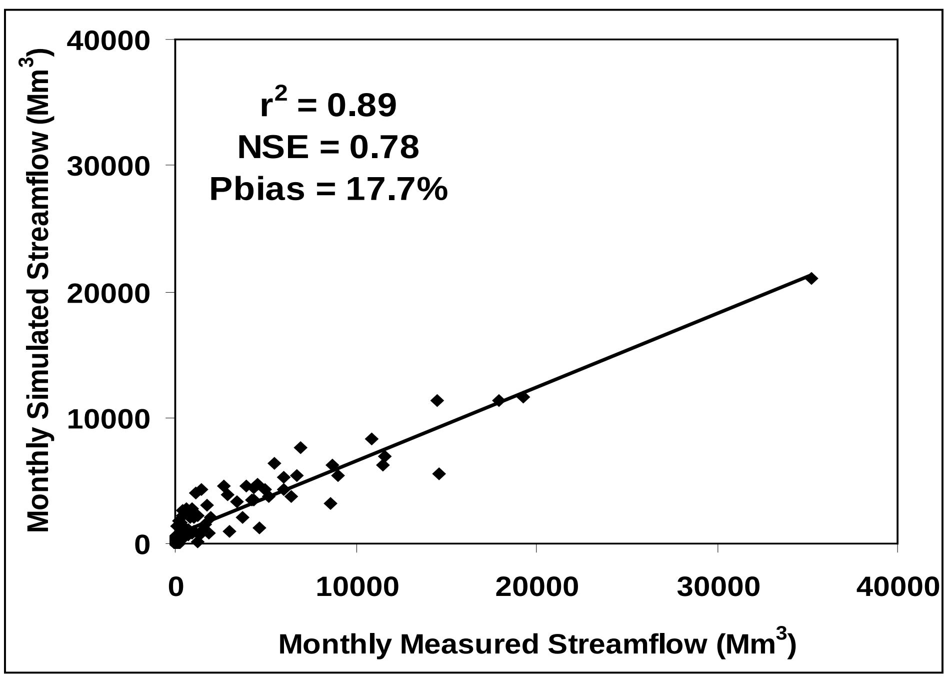


Figure 7. 2: Goodwater Creek Experimental Watershed (GCEW) divided into 8 subbasins with stream weirs, weather station, rain gauges, and streams.

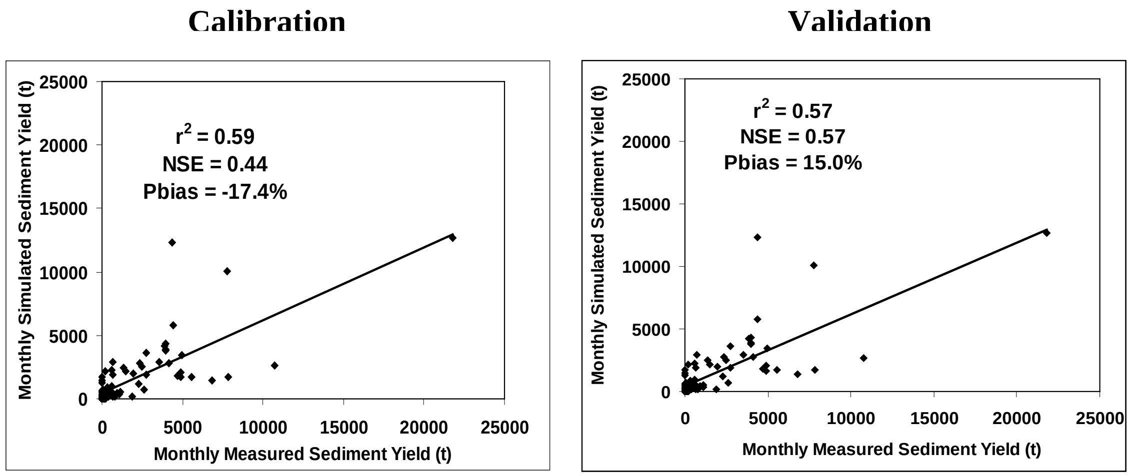


(a)

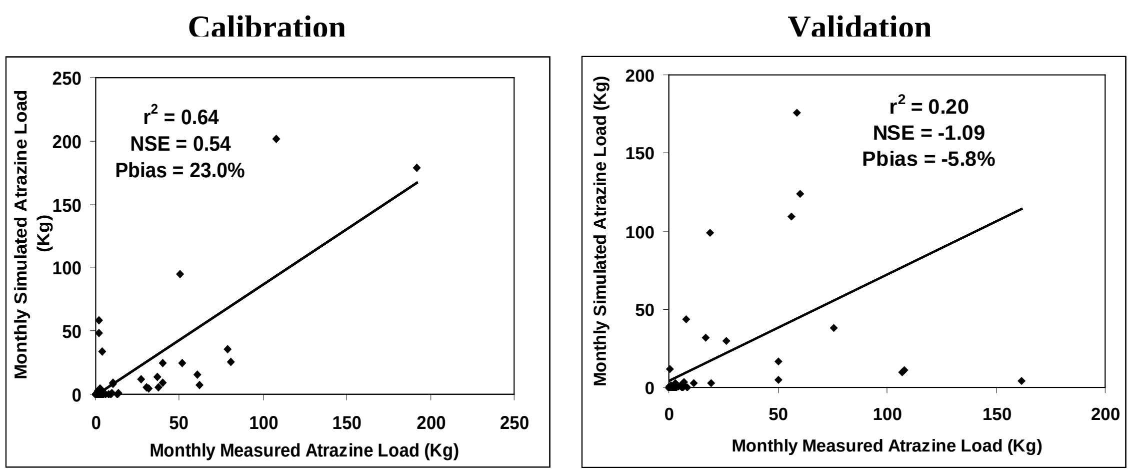


(b)

Figure 7. 3: Scatter graphs for monthly (a) calibration and (b) validation values for streamflow.

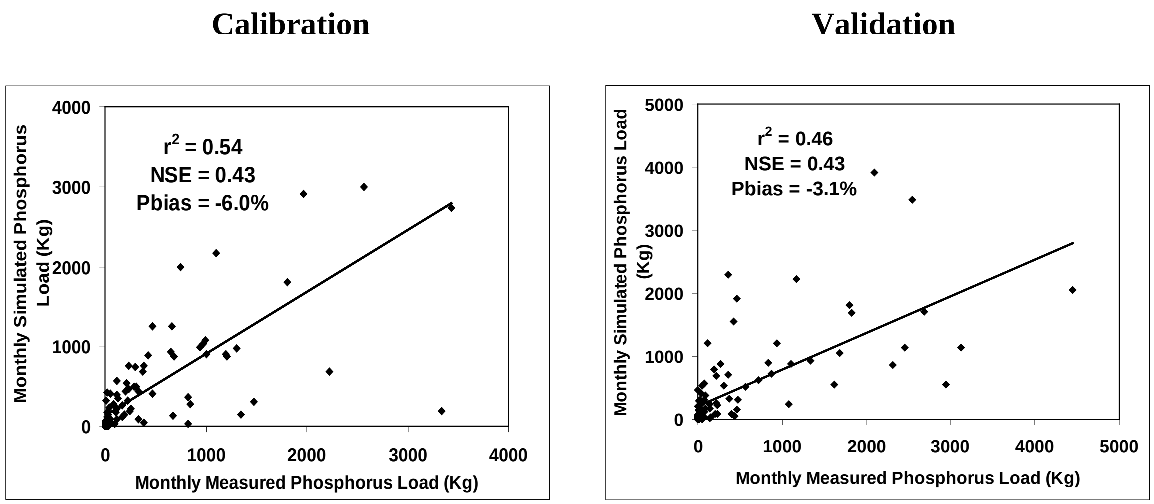


(a)

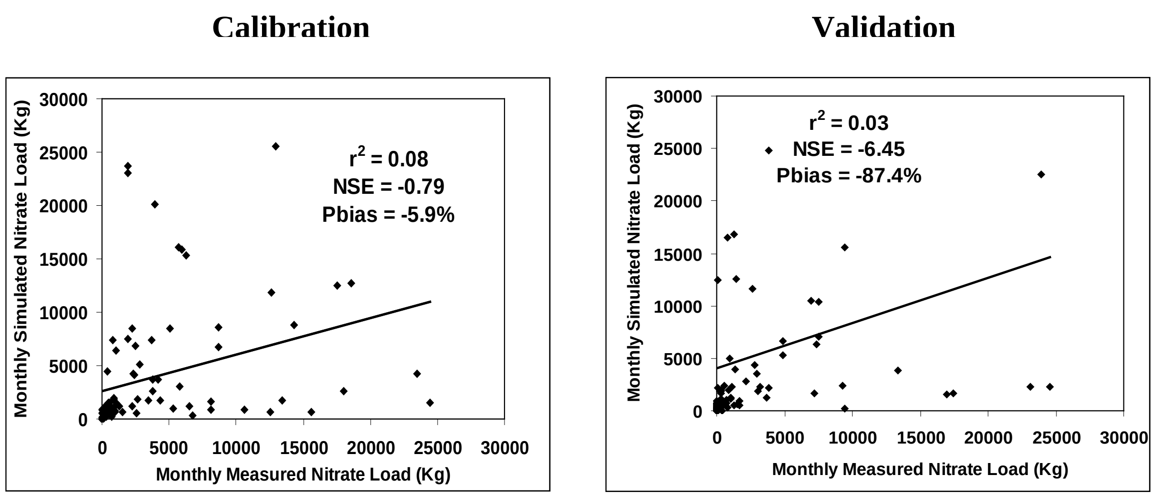


(b)

Figure 7. 4: Scatter graphs for monthly calibration and validation values for (a) sediment yield and (b) atrazine load.



(a)



(b)

Figure 7. 5: Scatter graphs for monthly calibration and validation values for (a) phosphorus (PO3-P), and (b) nitrate (NO-3-N) loads.

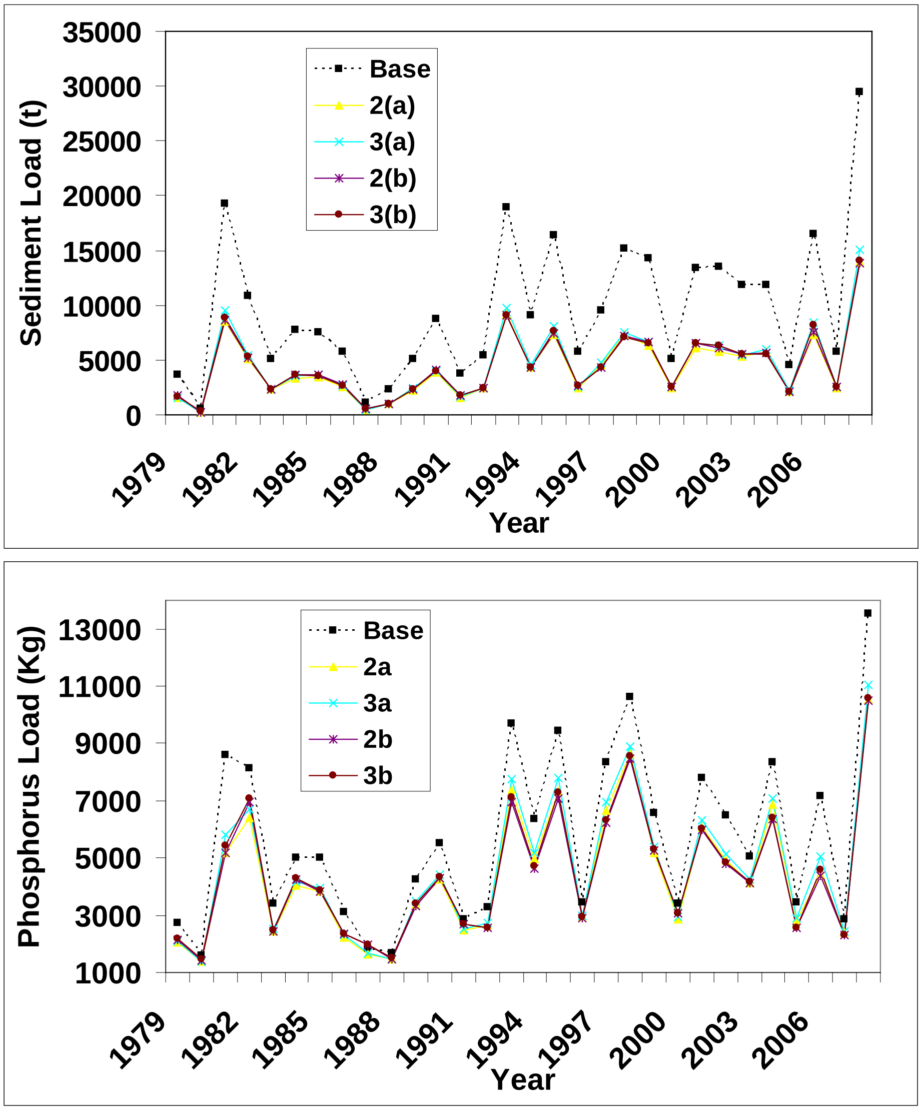


Figure 7. 6: Thirty year annual simulated (a) sediment yield, and (b) phosphorus load at the watershed outlet for five different scenarios.
Scenario 1: Base - baseline with no BMPs.
Scenario 2a: CMAs delineated by using model SWAT. Scenario 2b: CMAs delineated by using index CCI. All CMAs were placed under three different BMPs: filter strips (FS), grassed waterways (GWW), and terraces. Three BMPs were distributed among CMAs similar to the current distribution of BMPs in the watershed.
Scenario 3a: CMAs delineated by using model SWAT. Scenario 3b: CMAs delineated by using index CCI. All CMAs were placed under three different BMPs: filter strips (FS), grassed waterways (GWW), and terraces. CMAs with average slope greater than 3% were put under terraces. CMAs with slope less than 3% were divided into two equal parts based on area; one half received FS and the other half GWW.

CHAPTER 8

CONCLUSIONS

Critical management areas (CMAs) generating higher amounts of runoff and non-point source pollutants, and producing lower crop yields were delineated on plots and one field ontaining claypan soils (fine, smectitic, mesic Aeric Vertic Epiaqualfs and Vertic Albaqualfs). Later, these results were extrapolated to the watershed scale using the Goodwater Creek Experimental Watershed in northeastern Missouri. These CMAs were targeted for various best management practices in order to reduce runoff and non-point source pollutants and enhance crop yields.

The following conclusions were determined from the five studies conducted for this project:

Study 1: Impact of crop cover and management on soil properties

Two different management systems were selected for this study: a native prairie that has never been tilled (Tucker Prairie; TP) and a field that has been under row crop cultivation for more than 100 years (Field). Measured soil water retention curves showed that the Field site had lower soil water content for all pressures above -33 kPa; but for pressures at and below -33 kPa, water content was higher at the TP site for the top two soil layers only (0 to 10 cm and 10 to 20 cm). Coarse (60 to 1000 μm effective diam.) and fine mesoporosity (10 to 60 μm effective diam.) values were lower for the Field site (0.044 and 0.053 $m^3\ m^{-3}$) and were almost half those for the TP site (0.081 and 0.086 $m^3\ m^{-3}$). Bulk density at the TP site for the surface soil (0 to 10 cm) was 0.81 g cm^{-3}, which was two-thirds of the value at the Field site (1.44 g cm^{-3}). Bulk density at the TP site was significantly different than values at the Field site for all except the third depth

(20 to 30 cm). Saturated hydraulic conductivity (K_{sat}) was almost 57 times higher at the TP site (316 mm h^{-1}) than at the Field site (5.55 mm h^{-1}). This difference was likely caused by the differences in porosity and bulk density.

Selection of various soil and water conservation practices and their efficiency depends upon soil hydraulic properties. This study concludes that soil hydraulic properties are significantly different for the same soil series when fields are under substantially different management. Therefore, soil hydraulic parameters used for predictive purposes should be adjusted based on soil management in addition to soil mapping units.

Study 2: Assessment of landscape positions in claypan soils at the plot scale

The APEX model was able to simulate runoff and atrazine losses from agricultural plots in a claypan area as indicated by the selected goodness of fit criteria. For daily runoff, r^2 and NSE values varied between 0.55 – 0.98 and 0.46 – 0.94, respectively; for daily atrazine loads, r^2 and NSE values ranged between 0.52 – 0.97 and 0.45 – 0.86, respectively.

Landscape sequence analysis showed that the sequences ending with a backslope produced the most runoff and atrazine loss. Seasonal runoff and atrazine loads were highest and increased significantly by 83 and 72%, respectively, when the backslope length was increased by 20% relative to its original length. In this study, the critical characteristics that separated the summit, backslope, and footslope positions from each other were the landscape geometries (slope and length), depth to claypan, and hydraulic conductivity above the claypan. The latter two parameters were also found sensitive in the APEX model for runoff and atrazine load estimation. These findings could allow land managers and conservationists to delineate critical areas based on depth to claypan and saturated hydraulic conductivity and to test alternative management systems for these areas with the APEX model.

Study 3: Estimation of parameters for delineating CMAs at the field scale

The APEX model was calibrated and validated for runoff, sediment yield, and atrazine load at the field outlet from 1993 to 2002. The model was able to simulate these parameters within acceptable limits. The average annual runoff, sediment yield, and atrazine load as well as corn and soybean yields were estimated for all 35 subareas during the total simulation period. The subareas that were generating the highest amounts of runoff, sediment yield, and atrazine load were considered as CMAs. The total critical management areas delineated were 55% (17.3 ha) of the total field area (32 ha) because of all the three model outputs. Thirty-four percent (10.8 ha) of the total field area was found to be critical because of excess runoff generation, 33% (10.2 ha) because of atrazine load, and 6% (2.0 ha) due to sediment yield.

Two indices, the CPI (Claypan Index); calculated by dividing the Clay Depth by the average Slope and the CCI (Conductivity Claypan Index), calculated by multiplying CPI by the surface saturated hydraulic conductivity, were estimated for all the subareas. Significant correlations were found between the APEX model estimated runoff, sediment yield, atrazine load, and corn yield and these indices. Therefore these parameters were also used to estimate CMAs in the field. Index based delineation of CMAs captured 80% of the CMAs delineated by the model simulation technique. The CMAs delineated within the field were also found to be low corn yield producing areas.

Study 4: Impact of long-term cultivation on runoff, sediment yield, and atrazine load, and corn and soybean yields

Using two sets of soil profiles and soil properties, four simulation scenarios were developed to represent current conditions, original or enhanced conditions, and two alternative states that correspond to the improvement of the soil properties and the increase of the top soil depth relative to current conditions.

A calibrated and validated APEX (Agricultural Policy Environmental eXtender) model for daily runoff, sediment yield, and atrazine load was used to simulate the four scenarios under a corn-soybean rotation with mulch tillage. Based on thirty year (1978-2007) simulations, average annual atrazine load was reduced and average annual soybean yield was increased significantly for scenarios with enhanced soil properties in comparison to the baseline. The corn yield was significantly increased only with original conditions in comparison to the baseline. On the other hand, there was no significant reduction found in surface runoff and sediment yield for any of the scenarios in comparison to the baseline; but the scenario with current soil properties and profile had 51% of field area generating higher amounts of runoff in comparison to the maximum runoff generated by the scenario with an enhanced soil profile and improved soil properties. The scenario for field soil conditions when it was first cultivated, produced on average 40% higher corn and 39% higher soybean yields in comparison to the field under cultivation for over 100 years.

Study 5: Delineation of CMAs in the Goodwater Creek Experimental Watershed

Two indices, the CPI (Claypan Index) and the CCI (Conductivity Claypan Index) were used to delineate critical areas in the Goodwater Creek Experimental Watershed

(GCEW). A total of 2000 ha (25% of the total watershed) under agricultural land use excluding pastures had the lowest values of CCI and CPI and were delineated as CMAs. Both indices captured a similar area with only 300 ha not coinciding.

The calibrated/validated SWAT model from1993 to 2008 was used to simulate streamflow, sediment yields, atrazine loads, nitrate loads and phosphate loads for the GCEW. Both indices were able to delineate CMAs generating higher amounts of surface runoff, sediment yield, and sorbed herbicide and nutrient loads. CMAs were also found to have more numbers of days when the crop was under water and nutrient stresses.

Delineated CMAs were placed under three best management practices (BMPs): filter strips (FS), grassed waterways (GWW), and terraces. The scenario analysis results showed significant reductions in sediment yields and phosphorus loads, non-significant numerical reductions in atrazine loads, and insignificant changes in streamflow.

SUMMARY

The CCI and CPI indices were effectively able to delineate the CMAs at the field and watershed scales for areas with claypan soils; however for better estimation of CMAs, the type of management practice also needs to be included. Crop yields were also reduced in the CMAs. We conclude that further investigations are warranted to determine whether these two indices, CPI and CCI, can be used for delineating CMAs in claypan areas without the use of complex hydrologic models. The soil and topography data used to calculate these indices are accessible and can be used to delineate critical areas for targeting BMPs in claypan areas. Environmentally sensitive areas in claypan soils were also found to be areas with low crop yields. Therefore, land reclamation programs including CRP would be more beneficial in these areas because if these areas were taken out of agriculture to reduce their detrimental impacts on downstream water quality, the reductions in crop yield would not be as significant because of their lower than average crop yields.

Conclusion from the study evaluating long-term cultivation effects on watershed response were that the restoration of soil physical and chemical properties would not only increase crop yields but would also reduce atrazine losses at the field outlet. Management changes in CMAs would significantly reduce runoff and sediment yield. Therefore, after delineating CMAs, a holistic approach of improving soil properties and implementation of BMPs could not only reduce runoff and non-point source pollutants but would also increase crop yields.

VITA

Ashish Mudgal was born on April, 12, 1980 at Hisar, Haryana (India) to Dr. and Mrs. R.P. Moudgal. He received his B.Tech (Agricultural Engineering) in 2002 and M.Tech (Soil and Water Engineering) for CCS Haryana Agricultural University, Hisar (India). Soon after that he joined as a senior research fellow (Hydrology) at Central Soil and Water Conservation Research and Training Institute, Dehradun (India) in the project 'Impact of climate change on soil and water conservation'. In July 2010, he received the Doctorate degree in Soil Science from the University of Missouri, Columbia under the supervision of Drs. Claire Baffaut and Stephen H. Anderson. After graduation he would like to pursue work in soil and water conservation.