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Evaluation of APEX for Simulating the Effects of Tillage Practices in tropical soils

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By

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Evaluation of APEX for simulating the effects of tillage practices in tropical soils

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Tillage practices on agricultural fields have an impact on erosion levels and the hydrologic characteristics of the land. This erosion takes away soil that is necessary for sustainable agriculture The Llanos Orientales of Colombia is transitioning into crop production from cattle ranching or native ecosystems. This transition accelerates the degradation of soils, limiting the development of sustainable agricultural systems. As a first step to understand long term effects of agriculture in the region, this study evaluates the performance of the Agricultural Policy Environmental eXtender (APEX) model to simulate runoff, soil erosion and crop yield from fields under conventional, reduced, and no tillage. Calibrated APEX model predictions were compared against data from plots established in the Experimental Station la Libertad in Colombia. The calibrated APEX models showed satisfactory predictions for runoff and crop yield responses under different management practices but needs improvement for prediction of soil erosion in tropical soils.

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CHAPTER I

INTRODUCTION

Agricultural management has many implications on the soil erosion, runoff, crop productivity, and health of the land and surrounding ecosystem (Norcliff, 2002). Tillage practices are a major factor in the level of runoff and soil erosion occurring on the land and should be optimized to balance land and watershed health with crop productivity and economic gain (Lal, 1993). Especially in communities depending largely on agriculture for income, the economic cost of soil erosion is important to determine and understand. Long-term studies on soil erosion, runoff, and crop yield under different management can be time consuming and costly.

Modeling allows for a better understanding of the implications of different management practices and can help optimize them for the overall benefit of the environment and economy. By using models, previous understanding of systems can be applied to the characteristics of different management practices and the results can be projected for long-term decision-making.

Soil erosion affects crop productivity through the loss of nutrients, organic matter, affecting soil physics and chemical properties and other aspects of soil health related to the optimum development and growth of crops. To make up for nutrients deficit in the soil, farmers often apply more fertilizer or manure, leading to pollution and other negative environmental impacts. Tropical soils are especially susceptible to erosion, especially when used in agricultural application, and must be managed carefully to ensure long-term sustainability for the soils and surrounding ecosystem (FAO, 1965). In the Llanos Orientales region of Colombia, the soil is characterized as nutrient deficient because of the low cation exchange characteristics of the original rock that the soil comes from (FAO, 1965). These soils are historically used for cattle ranching instead of crop growth, with extensive livestock application in the region. However, with an increased food demand because of growing populations, these areas are becoming increasingly important for agricultural development. With proper management, the soils of the region can be productive and sustainable for crop growth (Basamba, et al., 2006).

Tillage is an important practice that can help support agricultural productivity in this area, but it can also cause further degradation to the already susceptible soils. One of the most significant effects of tillage on soil characteristics is on the soil structure. Tillage can change the porosity and particle size distribution, which in turn effects other characteristics, such as soil fertility and biodiversity. The soils characterizing the Llanos Orientales region are typically well drained, with higher levels of sand and silt. The particle sizes in these soils supports water retention in periods with less rainfall, and therefore allows them to support crop growth (FAO, 1965). By altering the particle size distribution, aggregates that help support proper water retention are disrupted and improper drainage can occur, as well as further erosion from the disruption of the fine soils (Lal, 1993). Because the soils in the Llanos Orientales region are susceptible to erosion and require additional nutrient inputs and other management to help ensure their productivity, the region poses a challenge to agricultural management with a balance between economic growth and social and environmental sustainability (FAO, 1965).

Agricultural fields growing soybean, corn, and rice on rotation at the Corpoica Experimental Station La Libertad were studied by Ramirez et al. (2001) under three different tillage practices:

conventional tillage, reduced tillage, and no tillage (direct planting). Modeling these management practices, especially when focusing on the sediment loads and crop yield, helps characterize the management practices with respect to erosion and soil fertility, and therefore provides a means to evaluate different management techniques to determine the best management practices for the area to maximize profit without depleting the natural resources. Overall, this study aims to evaluate the ability of APEX to model tillage management scenarios and their hydrological and environmental impacts on tropical soils of the Llanos Orientales in Colombia. Initially, a sensitivity analysis to identify the most sensitive parameters in APEX regarding the prediction of runoff, soil erosion, and crop productivity under the different management practices was completed. The analysis followed the Morris Method, which is a one factor at a time approach to modify the parameters and measure their effect on the modeled runoff, crop yield, and sediment yield. Following the identification of these parameters, collected data from field experiments, was compared to the model results using various quantitative statistics, including the Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and percent bias (PBIAS), to determine the model performance. Lastly, the comparison of the different management scenarios with respect to runoff, soil loss, and crop yield will be evaluated by comparing the results from each scenario. APEX has been tested extensively on soils in the United States (Bhandari, et al., 2016; Kumar, et al., 2011; Mudgal, et al., 2012; Ramirez, et al., 2017; Wang et al., 2012) and its evaluation on this research aims to better understand the model's ability to represent hydrology and watershed processes in tropical soils.

CHAPTER II

LITERATURE REVIEW

2.1 Soil Degradation

While focus has always been placed on controlling air and water quality, soil has recently begun to be recognized for its importance in a healthy ecosystem and environmental management programs have begun to emphasize soil health in the implications of different practices (Nortcliff, 2002). However, many activities and practices continue to threaten the health of this resource and soils are being degraded past the point of repair. In any application of soils, especially agricultural, practices must be established to ensure the sustainable use of soils, a healthy environment and a robust economy. Ecosystems operate through the relationships of natural processes and soil is an important part of this process and of overall ecosystem management (Doran, et al., 2002). With an increasing population, pollution is increasing and food demand is higher (Tilman, et al., 2011). This leads to more extensive agriculture that can increase erosion and other forms of pollution. In the last decade, 40% of the earth's land has been lost due to erosion, pollution, extensive cultivation, grazing, clearing, salinization, and desertification (Oldeman, 1992). Many of these causes of soil degradation have been focused and modified throughout history to increase productivity alone, without recognizing the importance of sustaining the many other functions of soil. However, everything is connected through nature and therefore, management practices must take every system into account (Doran, et al., 2002).

This includes understanding the social, economic, and environmental costs of every practice and including all environmental systems when evaluating the costs to the environment. The focus on agricultural productivity alone has furthered the issue of soil degradation, and has caused, and will continue to cause problems in the future if a more holistic approach to soil management is not considered and applied (Doran, et al., 2002).

2.1.1 Susceptible Soils

Soils can be more or less susceptible to erosion depending on their different properties and land management. Spatial variability within the of soils can make it difficult to completely characterize their overall susceptibility to erosion; however, certain common indicators of erodibility can be used to identify the most erodible soil and management activities can be concentrated in vulnerable areas (Veihe, 2002). Soil stability and degradation are affected by rainfall characteristics, therefore in tropical areas like Villavicencio, Colombia that have intense and extensive rainfall, both variables are very important to understand and take into consideration when evaluating management plans.

Most of the soils in the Llanos Orientales of Colombia are classified as Ultisols and Oxisols, characterized by having effective drainage, high salinity and aluminum toxicity. Nutrient deficiency in these soils causes difficulties supporting agriculture, especially when the soils are subject to the high temperatures and rainfall characteristics of the area (FAO, 1965). The high rainfall makes the soils less stable and can cause detachment, increasing erosion. Despite the limitations, soils from the Llanos Orientales of Colombia can be productive for the crops necessary to support the community and the economy (Basamba, et al., 2006). However, the increased management practices can also lead to increased soil erosion, causing more harm than good, eventually leading to even more infertility (Basamba, et al., 2006).

2.1.2 Causes of Soil Degradation

Soil degradation is a natural process that is exaggerated by certain management practices and other human induced changes to the soil structure and other properties of the soil. Natural soil degradation can include wind and water erosion and physical degradation, as well as non-structural chemical and biological degradation. Water erosion most commonly includes the loss of the topsoil, which is extremely important for the fertility of the soil. In extreme cases, water erosion can also affect the rooting depth of vegetation, increasing the vulnerability to degradation (Lal, 2001). Gully formation is another type of land deformation that can occur due to water erosion and has negative effects on the necessary processes for productive soil. Wind erosion is most critical for larger, coarse particles and is caused by a loss in the vegetative coverage. Like water, wind erosion can cause loss of important topsoil and can lead to terrain deformation in serious cases (Oldeman, 1992). Other than erosion, physical degradation that can occur on soils includes extensive compaction and crusting, as well as waterlogging and other issues related to drainage properties of the soil. Chemical degradation is also critical for many soils and occurs in many agricultural areas. Loss of nutrient availability and organic matter can occur because of the chemical degradation and salinization is a result of improper irrigation or proximity to saline water. Acidification and other forms of pollution are also degrading for soils through over application of fertilizers or off-site pollutants (Oldeman, 1992). Erosion can exaggerate this chemical degradation through loss of particulate nutrients in the eroded soil and loss of organic matter, especially in the eroded topsoil. Biological degradation includes the loss of soil biodiversity and the reduced ability for soil to support the ecosystem in different roles (Lal, 2001). Soils support populations of microorganisms that are crucial for a functioning ecosystem through nutrient cycling, waste disposal, and pollutant removal and if these microorganisms are affected by biological degradation, toxins can build up in the soil and the nutrient management will not be stable. Erosion can speed up the process of biological degradation because of its impact on soil organic matter and the loss of top soil, exposing lower layers that are not as habitable for microorganisms. Tillage specifically has an impact on the biological role of soil and can encourage microorganism communities when applied properly. Populations of larger organisms like earthworms can be harmed by tillage and there are often short-term benefits for smaller microorganisms; however, after extensive tillage over a long period of time, microorganism populations have been found to suffer and recovery of those populations can be difficult (Misha and Dhar, 2004).

This physical and chemical degradation of soil can be caused by many different processes: natural and man-made. Removal of vegetation, overgrazing, and over exploitation by agriculture or other industries are some of the primary man-made causes of degradation while climate, vegetation, and natural soil types and characteristics govern the natural causes of soil erosion (Rachman, et al., 2003). Many studies have been conducted to better understand the properties of soil affected by different management, and the effect of those properties on soil erosion. The soil strength, aggradation, and bulk density are identified as properties susceptible to changes in management, as well as properties that can help predict the level of soil erosion, as discussed above. A study conducted by Rachman et al. (2003) in Columbia, Missouri found that long term continuous crops were more susceptible to loss in soil strength and aggregate stability than those on rotation. Tillage applied to these crops also affected these properties that are significantly related to soil erosion and increased tillage resulted in increased erosion rates (Rachman, et al., 2003). Deforestation and other vegetative coverage removal can also increase the rate of soil erosion and was found to do so by 127% in a study conducted in Spain in Lithic Haplozeroll soil (Castillo, et al., 1996). Likewise, a study completed in Sichuan, China found that the cover factor of land is critical for soil erosion, and that if the land goes without vegetative cover, 98% of the watershed would be exposed to extreme levels of erosion. However, if the land was covered with dense vegetation, only 0.4% would be subject to high levels of erosion (Zhou, et al., 2008). Among many man-made processes that increase soil erosion, mechanization through tillage has been found to increase erosion in many cases and must be applied strategically to support the soil without causing erosion.

2.1.3 Tillage and Soil Erosion

Tillage can help support agricultural productivity when applied properly but it can also cause further degradation to the already susceptible soils. One of the most significant effects of tillage on soil characteristics is on the soil structure. Tillage can change the porosity and particle size distribution, which in turn effects other characteristics, such as soil fertility and biodiversity. Studies conducted in other tropical areas in southern Brazil and Paraguay, with similar soils to those present in the Llanos Orientales of Colombia, found intense erosion when conventional tillage was applied. Due to the change in particle size from the tillage and high rainfall in the areas, the average erosion was greater than 50 Mg/ha/year (Wingeyer, et al., 2015). Many studies have measured the effects of implementing reduced tillage or no tillage practices on these areas showing large levels of erosion, and most have concluded that reduced tillage protects the soil from erosion by maintaining a more natural porosity for water retention and a more stable particle size distribution (Wingeyer, et al., 2015, Basamba, et al., 2006, Unger, et al., 1991, Cadavid, et al., 1998. Czapar, et al., 2015, Nyamadzawo, et al., 2014).

Tillage not only effects the amount of erosion, but also causes changes in the amount of nutrients available in the soil. The disruption in particle size from tillage can cause a decrease in soil organic carbon, and the loss of the top soil to erosion also reduces the soil organic matter.

No-till practices were also applied to the areas studied in Brazil and Paraguay, and a significant increase in soil organic matter was observed over time. Other positive effects of no-till or reduced tillage systems versus conventional tillage include an increase in carbon dioxide respiration, increased stability (a product of more natural particle size distribution), and increased infiltration rates (Wingeyer, et al., 2015). In the region of the Llanos Orientales of Colombia, no-till systems were shown to have higher carbon and nitrogen values in the soil versus soils subject to minimum tillage systems (one chisel pass at 30 cm depth). Soil organic matter values were also greater in the no-till fields because of the limited soil disturbance when compared to the minimum tillage system. Phosphorus availability also varied between the different tillage practices. Biologically available phosphorus, H_2O- Po, showed higher levels under minimum tillage versus no tillage. This phosphorus is the first to be taken up by the plant roots and provides short term supply. Sodium hydroxide extractable organic phosphorus, NaOH-Po, is available for plant uptake in a longer term, and showed higher levels when some tillage was applied. However, other short-term available phosphorus, sodium bicarbonate extractable organic phosphorus were in higher levels under no tillage. These nutrients are important in the soils of the region, because they are traditionally characterized by lower nutrient levels and therefore soils are not expected to be as productive as in other regions. Overall, the no-till systems resulted in higher soil organic matter and phosphorus fraction values longer term; however, the difference in these values was not as significant as other nutrient values. While the no-till systems produced higher nutrient values, the crop yield was lower overall when compared to minimum tillage systems (Basamba, et al., 2006).

While no-till systems offer many benefits to soil health and stability, proper use of tillage practices can help increase soil fertility and can be beneficial to overall productivity. For example, the landform variations that result from certain levels of tillage can help the soil resist erosion from wind, especially if the direction of the ridges is planned according to typical wind orientation. Using a chisel instead of a harrow or other tools in conservational tillage can also help keep heavier and nonerodible soil at the surface, preventing further wind erosion. For the sandy soils present in the Llanos Orientales region, conservational tillage efforts can help increase the surface roughness that is lost after heavy rain. Likewise, ridges can help reduce runoff and therefore reduce water erosion (Unger, et al., 1991). When tillage is accompanied with residue or mulch cover, soil erosion can be further reduced, and the soil structure maintained. The plant cover can also support the reduction in soil temperature, which is important in tropical regions like Colombia. In Northern Colombia, Magdalena specifically, a study was conducted to compare different levels of tillage and different levels of mulching. On the fields in which mulch was applied, for zero tillage and conventional tillage, yield increased. Zero tillage alone showed the lowest yield; however, when mulch was applied, it showed higher yield than conventional tillage. The level of fertilizer was also varied for the study, and when fertilizer was not applied, the increase in yield with mulch application was significant. Likewise, the level of nutrients in the soil was much higher with mulch application, for both systems of tillage and with and without fertilizer (Cadavid, et al., 1998). Even without additional mulch application, conservational tillage typically leaves more crop cover than conventional tillage and was found to reduce the amount of particulate phosphorus loss, also reducing the phosphorus transport. Conservational tillage also reduces runoff, which can help reduce erosion, because of the crop cover that remains on the surface. Specific estimations for nutrient enrichment ratio are 1.5 in the sediments under no-till practices and 1.0 in conventional tillage. Nitrogen losses in eroded material under no-till and conventional tillage were estimated as 6.1 and 32.8

pounds/acre, respectively and for phosphorus are 2.4 and 12.7 pounds/acre (Cadavid, et al., 1998).

Economic evaluation of different tillage practices also found that conservational tillage practices were more profitable because of the reduced production costs and the increase in soil fertility (Czapar, et al., 2015). Utilized efficiently and planned according to the characteristics of the soil, tillage can help support a healthy soil ecosystem, but without determining the best management practice for tillage and applying that practice, it can quickly lead to a loss in soil quality and quantity and therefore a loss in productivity. To determine the best management practices for soil health and erosion reduction, it is important to understand the properties and effects of common practices. In the rural farming community of Chiota, Zimbabwe, climate change has led to crop failure in many traditional areas of farming. The community has turned to seasonal wetlands for cultivation, and the properties of these wetlands and their management is an important area of study for the future of farming in Zimbabwe and other countries in Sub-Saharan Africa. Rather than studying different practices of tillage only, burning, clearing, clipping, and conventional tillage were analyzed for their effects on soil organic carbon, nitrogen, phosphorus, and overall erosion volume. Consistent with many other studies, conventional tillage produced the most erosion and resulted in the least amount of soil organic carbon. Many of the other soil nutrients were lost under conventional tillage, and the study suggests the addition of manures to increase fertility in areas under tillage. (Nyamadzawo, et al., 2014). While most tillage practices are sustainable for a certain period, the risk in not identifying a best management practice to control soil erosion and other properties is that the soil will be degraded to a critical point, in which it is no longer able to support agriculture or even natural plant growth (Lal, 1993).

2.1.4 Effects of Soil Degradation

Soil degradation can be detrimental to many natural and man-made processes, most notably agriculture. Without healthy soils, crop yield will be reduced, and significant loss of production is realized. Especially in areas with extensive agriculture, as in this study area, soil degradation causes a loss of fertility that leads to more intense agricultural practices to try to increase crop yield and soil degradation will continue. To meet the food demands of a growing population, more natural lands are being converted to agricultural and pasture land, furthering the degradation and increasing the need for newer, more fertile land (Oldeman, 1997). Until this cycle is stopped, the soils will continue to degrade beyond the point of remediation. This puts global food security at risk and threatens many ecosystems. Loss of soil in general and loss of nutrients in the eroded soil reduces crop yield and impacts food availability. The global rate of erosion from cropland was over 6 Mg/ha/year as of 2009 and approximately 10 million hectares are estimated to be lost every year (Ye and Ranst, 2009). A national study completed in China modeled and evaluated predicted yield loss in a 20 and 40-year projection under different levels of increasing soil degradation. If the current rate of degradation is continued, they found that there would be an 11% yield loss by 2030 and a 15% yield loss by 2050. If soil degradation rate doubles because of increased agriculture and other management decisions, approximated 17% of yield is expected to be lost by 2030 and 30% by 2050. These predictions are based on a calibrated model for current degradation and yield losses and represent trends internationally under changing climate and current and predicted agricultural management (Ye and Ranst, 2009).

Because soil is a crucial resource for the support of life on Earth, its degradation and erosion can have severe impacts on not only agriculture, but also on many other ecological processes. With the erosion of the fertile topsoil, nutrient imbalance and habitat destruction are primary environmental concerns of soil erosion (Oldeman, 1997). Loss of biological diversity of the microorganisms living in the soil can occur when soil is degraded, specifically the loss of the fertile topsoil containing many of the active communities. Microbial communities suffer from disturbances from tillage and other practices, loss of soil cover, and loss of root strength and plant cover. Overall soil health is also indicated through these factors, concluding that microorganism populations are important indicators for soil health and are negatively affected under poor soil health. A study completed in Texas found that when soil erosion was reduced through various conservation techniques, the microbial communities increased. The stress on these communities was also measured through fatty acid methyl ester profiles and the stress on the existing communities decreased with increased erosion prevention measures (Li, et al., 2018). The health of microbial communities is important to support healthy plant growth and other ecological functions of the soil and the understanding of different impacts of soil erosion on not only the overall health of the soil, but also specifically on the health of these communities, is important in developing an integrated approach to increasing soil health and supporting the surrounding ecosystem (Mishra and Dhar, 2004). Soil erosion reduction is also important to protect surrounding communities, especially in aquatic systems.

Following the erosion of fertile topsoil, the effects that the eroded material has on the surrounding waterbodies and other natural systems, in terms of nutrients and other pollution, are secondary environmental concerns. Because of fertilizer and pesticide application, many soils contain chemicals that are transferred into the surrounding environment when soils are eroded. The fertilizer and pesticides can also run off into the water bodies or leach into groundwater, even if erosion rates are not high. However, the sedimentation that occurs because of eroded material entering the surrounding environment has many negative impacts and can cause environmental and economic damages (Karlen, et al., 1997). Sedimentation from soil loss is detrimental to many communities, clogging up rivers and other water bodies and reducing fish populations through loss of available habitat and food. Many conditions that lead to increased soil erosion are also likely to increase runoff because the soil has less retention capacity. This increased runoff can lead to flooding and other damaging effects and will negatively affect the community and will exaggerate the already problematic conditions of the ecosystem from nutrient and sedimentation pollution (Karlen, et al., 1997).

2.2 Costs of Soil Erosion

The costs related to soil erosion include productivity loss, environmental and social costs. These costs are related and understanding each component helps quantify the others. Together the costs point out the negative impact that soil erosion creates, especially in agricultural communities (Cohen, et al., 2006). Tillage practices can accelerate the process of soil degradation, effecting the soil stability, resilience, and quality of the soil (Lal, 1993). Quantifying the costs that occur under each tillage practice can lead to a better understanding of the processes of soil erosion and can help identify the focus of restoration activities and the best tillage practices for soil preservation, increased productivity, and increased environmental protection.

2.2.1 Productivity

Soil productivity is one of the most important factors of soil management with respect to the human population. Without productive soil, none of the resources that we need to survive would be available. This productivity is based on several factors and is very sensitive to many components of soil management. Erosion can reduce this productivity and management practices should aim to control erosion to preserve the many properties of soil that are important for its productivity. Organic matter content, soil-depth, aggregation, texture, respiration, bulk density, infiltration, nutrient availability, and retention capacity are all cited as the most important indicators for soil productivity (Arshad and Martin, 2002). If these properties are not allowing the soil to function as productively as desired, additional inputs are necessary. The additional inputs exert economic and environmental costs and cause the soil and the overall agricultural production to be unsustainable. Therefore, activities that alter the characteristics important to soil productivity are important to manage to optimize productivity. Organic matter content affects soil productivity by changing the soil structure, water retention, and nutrient content. This also influences the base saturation and pH of the soil, which are important parameters for crop growth. The nutrient levels in the soil are extremely important for soil productivity and with a loss in nutrient levels due to erosion, inputs that can be harmful to the environment are necessary (Kimetu, et al., 2008). Tillage effects this organic matter content through the loss of topsoil following erosion and through particle size disruption (Wingeyer, et al., 2015). The topsoil contains vital organic matter for plant growth and productivity, and this topsoil is especially susceptible to erosion following tillage or other disturbances.

The soil-depth is important for the root development of plants and for the nutrients available at different levels, making it an important factor in soil productivity. As with the organic matter content, the loss of the topsoil layer and reduction in soil depth decreases soil productivity, especially if the subsoil is not supportive of crop growth. Root depth can reach a limiting layer in soils, in which productivity is declined. The soil depth can help predict the soil's vulnerability to loss of productivity following erosion and shallower soil depths have been found to have greater losses in productivity following erosion (de la Rosa, et al., 2000). Better managed tillage practices can help reduce the loss of soil depth and therefore can help prevent increased loss in productivity following erosion.

Soil aggregation and texture affect and can help predict many other soil properties related to soil productivity. Water content and retention is affected by the aggregation and texture, and other structural components of the soil are dependent on the aggregation. More diverse soils are more productive and as stability increases, susceptibility to erosion decreases and productivity increases. Properly applied tillage can help increase the diversity and structural components of the soil; however, when applied unsustainably or in excess, tillage can have a negative impact on soil structure by decreasing the diversity and increasing the instability (Lal, 1993).

The many components of soil structure and soil chemistry are related and greatly affect its susceptibility to erosion and to the loss of productivity following erosion. Because of these sensitive relationships, soil erosion can disrupt the system and greatly affect the productivity of agricultural soils. When the structure of the soil is disrupted, through tillage or other disturbances, erosion accelerates, and productivity is reduced. However; when applied to the soil properly, tillage can also increase the productivity of the soil by improving the structural characteristics of the soil and increasing the biodiversity (Lal, 1993). Therefore, with respect to soil productivity, management techniques must be balanced to ensure biodiversity without disrupting the soil to the point of erosion and loss of productivity.

2.2.2 Environmental Cost

Soil erosion can result in many negative environmental impacts, especially in tropical areas with increased susceptibility to erosion in general and high levels of precipitation throughout the year. Costs to the agricultural land include loss of sediment and the loss of nutrients in the soil and water. Many off-site costs also occur from soil erosion, including soil detainment and loss of ecosystem health (Cruz, et al., 1988). Most critically, erosion causes an increase in sediment in the runoff and surrounding waterbodies. Erosion can also lead to increased nutrient levels in the surrounding ecosystem, which can lead to eutrophication and other problems downstream. This disrupts the overall watershed and greatly reduces the functionality of the ecosystem. These costs are important to quantify when understanding different management techniques as some practices that may be better for productivity do not result in the least environmental costs. The costs must be balanced to ensure the most productive and healthiest soil system, and the environmental costs are some of the most critical components of this management focus (Chen, 2011).

Soil erosion from upstream agriculture causes increased sedimentation and turbidity in downstream waters. This turbidity affects the ecosystem through harming the habitat for many organisms and altering food availability. This in turn threatens the biodiversity of the watershed and can greatly reduce the health and resilience of the ecosystem surrounding the agriculture. With increased sediment, especially organically rich sediment from treated agricultural land, biological oxygen demand increases, and the dissolved oxygen concentrations decrease. This alters the balance of the ecosystem and puts many organisms at risk. Light penetration into the water is also affected by increased turbidity, which reduces the production of oxygen by aquatic plants and impacts their populations. Turbidity and suspended sediments can also cause aquatic species to be more susceptible to disease by collecting in their gills and entering their systems. Settle particles can also harm the eggs on the bottom surface and reduce the population of many species relying on the stream bed for reproduction (DFO, 2000).

When erosion occurs and productivity decreases, increased nutrient input is often necessary in the form of fertilizers to help increase the crop growth. This application can cause the sedimentation of eroded materials to be even more harmful to the environment, as they carry pollutants and transport them to the downstream systems. The most significant impact of the increased nutrient levels in the water is eutrophication. Because of the nutrients, there is increased aquatic plant growth, reducing the oxygen levels in the water and harming populations of other organisms (Nyamadzawo, et al., 2014). Likewise, increased tillage activity can cause higher nutrient levels through the change in soil structure and through the larger volume of eroded material. When applied strategically, however, the fertilizers can help increase productivity without causing harm to the environment through eutrophication and other issues. It is therefore important to determine and understand every component of the cost of soil erosion under different management techniques and to apply this understanding to implement the best strategies for overall crop, environmental, and economic benefit (Nyamadzawo, et al., 2014).

2.2.3 Socioeconomic Cost

Because many people in rural areas rely on agricultural for a large portion of their income, the issues of productivity following soil erosion are also economic and social issues for many farmers and communities. When soil productivity is reduced because of the factors discussed above, crop yield is limited, and increased inputs are necessary. Therefore, farmers are having to spend more on their crops but are earning less income because of their limited yields. The management practices used to control the soil and regulate sustainable yield also require monetary input and human labor, and these costs must also be considered when measuring the overall costs of erosion and the overall costs and benefits of different management techniques to control this erosion (Holland, et al., 2010).

In many situations, farmers and other actual users of the soil are only concerned with the on-site costs of soil erosion, including the sediment, nutrient, and water loss that leads to loss of productivity. Even if farmers implement management practices to help control these losses, they often apply them only to the extent that it is economically beneficial for them personally. However; some of these management practices (including increased fertilizers for higher yield) can have a negative impact on downstream water quality and can lead to other off-site costs. While these off-site costs are not placed on the farmer, someone must pay for them. This leads to loss of community resources and possibly to negative relationships between the community and the agricultural workers. Therefore, community input in decisions regarding management practices are important and consideration of all possible costs of different practices is crucial to balance economic, social, and environmental productivity (Holland, et al., 2010).

2.3 Modeling Agricultural Systems

The long-term effects of different management practices and scenarios is critical to maintain sustainable agriculture and a healthy environment. Modeling can predict what changes will occur under these different long-term conditions. Several models have been tested and applied to different environmental issues and are an increasingly important tool for environmental management. The Soil and Water Assessment Tool (SWAT) is one such model that has been used to further understand the impact of land use on soil and water quality and quantity. Like APEX, SWAT uses several inputs to estimate water balance and soil erosion, but only at the small watershed to river basin-scale. Field scale is not available in SWAT. SWAT includes the option to input point sources of pollution, climate data, land area and land use data, topography, hydrologic cycle information, and nutrient management information. It includes some variations in runoff estimation, curve number and Green & Ampt, and uses the equations based on the Universal Soil Loss Equation (USLE) to predict soil erosion (Arnold, et al., 2012). The European Hydrological System Model (MIKE SHE) is used to simulate watershed characteristics and processes including water movement, the effects of land use and management, and can be applied to any watershed size (Golmohammadi, et al., 2014). Other models, including the Annualized Agricultural Non-Point Source (AnnAGNPS), Hydrological Simulation Program-Fortran (HSPF), the Decision Support System for Agro Technology Transfer (DWSM), and others are designed to work with similar functions; however, APEX was chosen because of its applicability to the field-scale and the variations available for estimation parameters (Borah and Bera, 2003).

2.3.1 APEX

The Agricultural Policy/Environmental eXtender (APEX) can be applied at the field or watershed scale and simulates water, nutrients, sediment, and other parameters of interest in overall watershed management. It operates on a daily timescale and relates climatic conditions, management practices, and other field characteristics to the outputs of water movement, crop yield, nutrients, and sedimentation. APEX can operate using different runoff and soil erosion estimations including: the curve number method and Green and Ampt estimation for runoff and the Revised Universal Soil Loss Equation (RUSLE), the Modified Universal Soil Loss Equation for Small Watersheds (MUSS), and the Universal Soil Loss Equation (USLE) for soil erosion. These components of the watershed model are calculated using the specified equation and the climatic and other conditions that affect the runoff and erosion. It models the complete nitrogen cycle, including nitrogen uptake, mineralization, and organic nitrogen as well as phosphorus uptake and organic and mineral phosphorus. The crop growth is estimated as potential daily growth and includes stresses on growth given in the climatic and operation schedule input in the simulation (Wang, et al., 2012).

Many studies have been completed on the use of APEX on soils in the United States, and have found success in applying APEX to several different conditions to accurately describe and predict characteristics of the watersheds and fields like runoff, nutrients, crop yield, and sedimentation. While studies have been conducted in different areas of the world with different soils and climates, there is more to learn about the ability of APEX to characterize fields with certain conditions and for certain parameters. Learning about the use and ability of APEX in the United States and elsewhere and applying that knowledge to the tropical soils of Colombia, or to any different soils and climates around the world, will allow for the possible adjustment and improvement of the model for these varying conditions and desired modeled parameters.

APEX can characterize and predict many different responses of fields and watersheds to climate and management conditions, some of which have been tested more than others. Its ability to accurately predict many hydrologic properties has been tested thoroughly and runoff and nutrient loss characterizations have proved successful in many applications. As for example, a study conducted in the Mississippi Delta region of Mississippi tested APEX's ability to model fields growing cotton and soybean with varying soil types. The model was tested and calibrated for runoff, soil loss, and nutrient loss, and proved effective at modeling each parameter. Additionally, different management scenarios were compared using the calibrated model, including different levels of tillage and the presence of cover crops. This proved APEX's ability to not only model runoff, soil loss, and nutrient properties at the field and watershed scale, but also its ability to test different scenarios of management to be applied for conservational purposes (Ramirez-Avila et al., 2012).

To optimize the application of APEX, Wang et al. (2012) described the basic steps necessary for proper calibration and validation of the model for predicting runoff, crop yield, sedimentation, and nutrient loss. The authors described the first component to consider for calibration is the water balance. Guidance was also offered to perform adjustments to ensure a proper balance of the inflow and outflow of the water in the systems before more detailed calibration begins. A sensitivity analysis and literature review of sensitive parameters for runoff, crop yield, sediment yield, and nutrient loss are suggested as a crucial step to calibrate the most influential parameters for the model's prediction. Their study identified the most sensitive parameters for runoff prediction to be the initial condition curve number, the land use number, the curve number index coefficientand the potential heat units for the crops growth, among others. To calibrate crop yield, bulk density, the number of years before cultivation, plant population, and harvest index, are typically the more sensitive parameters. Erosion control factor, soil erodibility factor, are important parameters to consider for calibration of sediment yield.

Wang et al. (2012) conducted a field scale study and tested the calibration and validation of the APEX model, measuring performance with PBIAS, r^2, and NSE as statistical indicators. The model was calibrated for a certain period and validated for the remaining period of known data for runoff and atrazine loads and produced strong NSE and PBIAS results. The study concluded that accurate modeling of runoff, crop yield, sedimentation, and nutrient loss is possible using calibrated and validated APEX models (Wang et al., 2012).

Bhandari et al. (2016) completed a study that further evaluated the calibration and validation abilities of APEX for runoff, sediment, and phosphorus loss. This study not only determined the ability of APEX to calibrate data under similar management practices, but also determined its ability to use calibration data that is different from the modeled management. Two locations were used to test the calibration and validation and included fields under three and four different tillage practices, respectively. Using measured precipitation and runoff data from each site, models for the different management practices were developed and calibrated. Using manual sensitivity analysis and calibration, the models were tested using management specific calibration data and were modeled for different management practices. Under management specific data, the statistical analysis of the calibrated model showed positive results for accurate modeling of runoff, sediment, and nutrient loss. When using different management practice data for calibration, the model was able to accurately represent runoff, but in most cases did not produce desired results for other parameters. Each of the different tillage practices were analyzed individually and all proved to accurately model runoff and phosphorus loss under calibration data from similar management practices, but the sediment criteria for the model was not reached on all sites. Further analysis of sensitive parameters for more detailed calibration could provide more accurate results; however, this study concludes that with calibration data of similar management practices, APEX is capable of modeling runoff, sediment, and nutrient loss for different management practices (Bhandari et al., 2016).

The method of calibration and efficiency estimation is important for accurate representation and should be considered when applying the model to study areas. For a model to be useful, it must be able to predict the characteristics of the watershed or field under different conditions beyond the point of the known data. This known data should be used for calibration purposes and can determine the ability of the model to accurately represent the conditions of the watershed (Baufett et al., 2016). A study conducted in Kansas and Missouri examined the effects of using Best Professional Judgement (BPJ) parameterization instead of typical calibration with known field data to test the accuracy of the models. This BPJ parameterization consists of using regional weather and soils data and an overall understanding of the management scenarios, rather than using the actual known and collected data. This model application was compared to a model that utilized the traditional calibration techniques and the known data from the fields. For runoff, both the BPJ parameterization and the traditional calibration yielded satisfactory results, with calibration yielding more satisfactory Nash-Sutcliffe Efficiency values. While the runoff results were acceptable for both methods, sediment and nutrient yields were not accurately predicted using BPJ parameterization. Therefore, traditional calibration is recommended for more accurate estimation of both runoff, nutrient, and sedimentation in fields and using accurately collected data from the fields boosts the model's ability to represent the area (Baffaut et al., 2016).

APEX has proven effective in modeling both the erosion and the crop productivity from agricultural fields and has allowed researches to better understand the effects of different field parameters on erosion and the impact of this erosion on crop yield. The modeling tool was successfully used to help characterize long-term erosion impacts on crop productivity in China when long-term field monitoring was not feasible. With land use data, climate data, and management information, APEX was calibrated and used to predict changes in erosion and productivity and the relation of the two variables (Lin et al., 2016).

CHAPTER III

MATERIALS AND METHODS

3.1 Project Area

Available information for nine plots located at the Experimental Station La Libertad of the Colombian Corporation of Agricultural Research (CORPOICA) near Villavicencio, Colombia, were used in this study to simulate the effects of three different tillage practices on soil loss, runoff, and crop yield. The three different tillage practices include reduced tillage, conventional tillage, and no tillage. Each field has an area of 50 square meters with a 4% slope on average and each tillage practice was applied to three fields from 1996-1999. During this period, climatic data was collected and runoff, soil loss, crop yield, and other field characteristics were measured for inclusion in the model and for other analysis.

The runoff, soil loss, and crop yield data collected from the four years of the study period is used to calibrate the model to ensure its accuracy in characterizing processes and crop yield from the monitored fields and management practices. For each management practice, the three fields subject to the practice were averaged for the entire study period.

3.2 Model Set Up

APEX operates on a daily time-step and utilizes information regarding climate, soils, and management to determine the processes of water balance, crop yield, nutrient cycles, and erosion. Each management scenario was evaluated separately, using the average of the three fields with each tillage practice for the data input into the model.

Within the control files for APEX there are several methods to estimate evapotranspiration, runoff, and soil loss. The Hargreaves method was used to estimate evapotranspiration. This method was chosen as it applies to windy conditions and uses the daily maximum and minimum air temperatures. Potential evapotranspiration is an important variable in determining the crop evapotranspiration and daily estimations are necessary for proper characterization of the crop schedule and water balance resulting from the management (Cai, et. al., 2007). While it is cited as typically overestimating evapotranspiration, it has resulted in reducing the overall runoff when compared to other methods of estimation when the model adjusts the water budget (Trajkovic, 2007). The model also includes the parameters used in the Hargreaves equation, which can be calibrated for the most accurate representation.

The Curve Number (CN) method was applied in this study to allow the daily changes in soil moisture and other factors affecting the CN to be represented in the runoff estimation. The runoff is then daily estimated by:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \tag{3.1}$$

where P is the total precipitation depth (in) and S is the potential maximum retention (in), defined as $\frac{1000}{CN} - 10$, where CN is the curve number characterizing the land use and its retention.

To account for the variability of the CN, several options are considered in APEX. The variable daily CN using the soil moisture index was chosen for this study to represent the changes in the CN estimation based on soil moisture and land use. There is also a parameter included in the APEX input (Parm 42) that can be optimized for accurate estimation of the CN index coefficient. For the period following harvesting, the CN for fallow land was used. The CN varied for the period of crop growth, depending on the crop. The soil in the study area is in hydrologic group A and the CN used represented this group for each land use. Table 3.1 includes curve numbers used in the model.

Table 3.1 Curve numbers used in APEX

Tillage Practice	Land Use	Land Use Code	Description	Curve Number Value
Conventional Tillage	Pasture	25	Pasture (Good hydrologic conditions)	35
	Soybean, Rice, and Corn	13	Small grain contoured and terraced (good hydrologic condition)	59
	Fallow	1	Fallow straight row	77
Reduced Tillage	Soybean and Rice	13	Small grain contoured and terraced (good hydrologic condition)	59
	Corn	19	Close-seeded legumes or rotation meadow (good hydrologic condition)	51
	Fallow	2	Straight row crops (poor hydrologic condition)	72
Direct Planting	Soybean and Corn	24	Pasture or range (Fair hydrologic condition)	25
	Rice	2	Straight row crops (poor hydrologic condition)	72
	Fallow	1	Fallow straight row	77

The soil loss was estimated using the Modified Universal Soil Loss Equation for theoretical based estimation (MUST). This method was selected following a manual sensitivity analysis performed to evaluate how the estimation methods fit the data. The MUST method fit the sediment yield data most accurately as it showed higher sediment values than the MUSLE or

RUSLE equations. MUSLE, MUSS, and RUSLE all under predicted the sediment yields and resulted in several outliers in the monthly sediment data.

3.2.1 Management

The dataset for this study represented nine fields managed with varying tillage practices (conventional, reduced and no-tillage), by applying each of the three practices to three fields. Reduced tillage included one pass of a rigid chisel and one pass of vibrating chisel. Conventional tillage includes two passes of a spike tooth harrow and two passes of a rod weeder for each crop in each period. Reduced tillage consists of one pass of a vibrating chisel and one pass of a rigid chisel. No tillage includes direct planting with no tillage activities for each period. Other management conditions were kept consistent for the plots to accurately compare the effects from different tillage applications. This management included application of fertilizer and pesticide and the harvest of each crop at the end of the growing season. The crop growth on the fields included maize, soybean, and rice in rotation with rice planted in the first half of every year and soybean in the second half. In 1998; however, maize (variety Sikuani) was planted in the first half of the year for each of the study plots. This variety is tolerant to acidic soils and aluminum saturation and has a maximum root depth of about 1.5 meters and a harvest index, which is the amount of grain harvested over total biomass, of 0.35 (Unkovich, et. al., 2010). The optimal temperature for the crop growth is 25°C and the minimum allowable temperature is 10°C (Ramirez-Avila, 2001). The soybean varieties studied include Ariari 1 and Soyica P34. The minimum temperature for growth used in the model for this crop was 10°C and the optimum temperature was 25°C. Both varieties had average aluminum tolerance and a harvest index of 0.30. Oryzica Sabana 10 rice was planted for this study and is aluminum tolerant and resistant to extreme acidity. The harvest index included in the model was 0.25 and the optimal growth temperature was 25°C with a minimum temperature of 10° (Ramirez-Avila, 2001).

3.2.2 Climate

The weather data used for inclusion in the model and further analysis was collected during the study period by the CORPOICA through in-situ gauges and meteorological stations in the project site. Precipitation values were obtained from gauges and analyzed for return period and recurrence probability, shown in Figures 3.1 and 3.2 below. In cases of missed or inaccurate collection of rainfall data from the sites, data was compared to records from the climatic station La Libertad near the experimental site and missing values were filled in. Solar radiation was calculated from solar brightness recorded from the La Libertad weather station and the duration of sunlight.

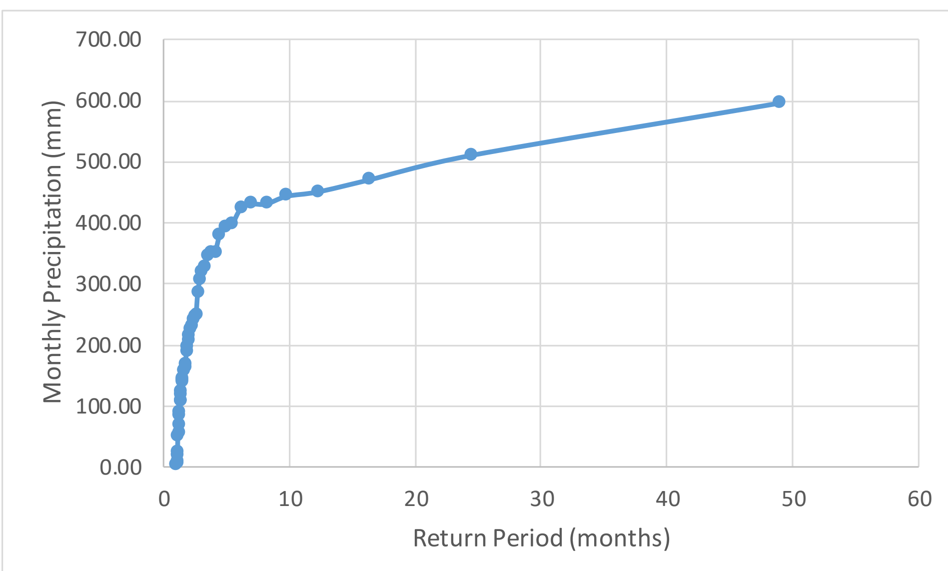

Figure 3.1 Rainfall Return Period

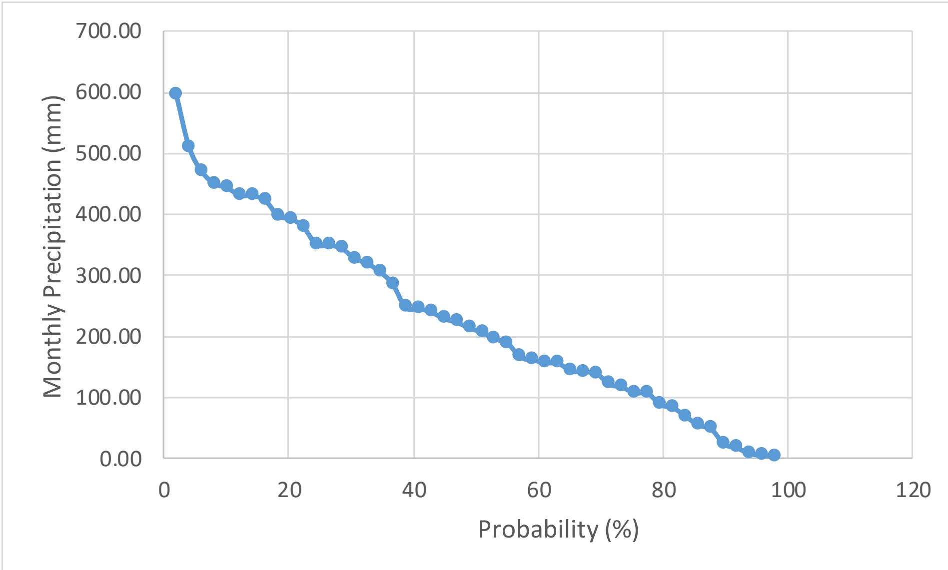

Figure 3.2 Probability of Occurrence

The climate in the region is classified as a Savanna climate, with clear seasons of rain and drought. The season of low rainfall is from December to March and the rainy season is from April to July. The average maximum monthly temperature recorded during the four years was 33.24°C in January and the minimum was 21.2°C in July and August. Average daily precipitation ranged from 0.48 mm in January to 15.0 mm in May. Annual precipitation for each of the years under study ranges from 2450 mm in 1997 to almost 3100 mm in 1996. The precipitation data is especially important for accurate modeling of the systems because it is a crucial factor in the characterization of runoff, soil moisture and composition, and many other properties of the fields under study (Ramirez-Avila, 2001). The average monthly weather data used in the model during the 4-year study period is included in Table 3.2 below.

Table 3.2 Average Monthly Weather Data

Month	Precipitation (mm)	Max Temp (°C)	Min Temp (°C)	Solar Radiation (MJ/m^2)	Wind Speed (m/s)
Jan	0.48	33.24	22.37	5.47	61.03
Feb	4.89	32.83	21.90	5.25	60.82
March	4.20	32.78	22.53	4.08	51.74
April	13.85	31.23	22.53	3.92	53.78
May	14.98	30.35	22.07	4.05	51.93
June	12.54	28.73	21.40	3.40	51.44
July	8.53	29.17	21.18	3.77	52.83
August	6.63	29.97	21.20	5.09	53.30
Sep	9.01	31.72	22.01	5.09	52.55
Oct	8.78	30.53	21.80	6.24	52.25
Nov	6.72	30.68	21.77	5.92	53.34
Dec	1.44	31.45	22.15	7.61	55.13

3.2.3 Soils

The soils data from each of the fields includes bulk density, sand and silt content, pH, organic carbon, water content, and others. Information about textural and chemical composition is critical in the characterization of the erosion, nutrients, and other properties of the land and surround ecosystem because of tillage practices. The soils were sandy, classified in the order *Tropeptic Haplorthox*, with approximately 65% sand content, 22% silt content, and 13% clay. These were soils that allow quick drainage and typically lower runoff. With an average pH of about 5, the soils were acidic. Bulk density of the soil was about 1.15 Mg/m^3 under reduced tillage, 1.20 Mg/m^3 for conventional tillage, and 1.40 Mg/m^3 for direct planting. Field capacity was around 0.25 m/m for the soils under reduced tillage, 0.3 m/m under conventional tillage, and 0.26 m/m under direct planting. The wilting point is around 0.18 m/m for each tillage practice, ranging from 0.17 to 0.19 m/m (Ramirez Avila, 2001). Some of the soil parameters included in APEX are shown in Table 3.3 below.

Table 3.3 Soil Parameters Included in APEX

Soil Parameter	Value used in APEX
pH	4.7
Bulk density (Mg/m^3)	1.21
Soil hydrologic group	A
Sand Content (%)	63.8
Silt Content (%)	22.7

3.3 Model Calibration and Validation

The average and yearly runoff, soil loss, and crop yield values from each practice reported by Ramirez et al. (2001) are included below in Table 3.4. Each management practice was applied to three fields and the average of the characteristics from the three fields was used in calibration. The data from 1996 and 1997 was used to calibrate the model while the period of 1998 and 1999 was used for validation.

Table 3.4 Runoff, Soil Loss, and Crop Yield for Three Management Practices from 1996-1999

		Reduced Tillage	Conventional Tillage	Direct Planting
Runoff (mm)	Average	243.98	153.30	134.71
	1996	79.12	92.86	81.27
	1997	241.31	153.35	87.29
	1998	142.5	114.94	81.62
	1999	512.97	252.03	288.67
Soil Loss (t/ha)	Average	4.26	3.64	2.81
	1996	4.51	4.03	1.21
	1997	5.90	6.24	3.39
	1998	1.01	1.01	2.11
	1999	5.61	3.29	4.53
Crop Yield (t/ha)	Rice	7.97	7.5	7.81
	Soy	4.09	2.24	1.92
	Corn	0.92	0.97	0.51

(Ramirez et al., 2001)

A sensitivity analysis was completed to determine the parameters included in APEX that should be calibrated and validated for runoff, crop yield, and sediment. This sensitivity analysis was completed using APEX_CUTE (Agricultural Policy Environmental eXtender-auto-Calibration and UncerTainty Estimator). APEX_CUTE uses the Morris Method for sensitivity analysis. This method uses a one factor at a time approach and varies the selected parameters through levels within a range of realistic values. The elementary effect of the changes in the parameter value is computed as:

$$u_i = \frac{Y(x_1,x_2,\ldots,x_i+\Delta x_i,\ldots,x_k)-Y(x_1,x_2,\ldots x_i,\ldots x_k)}{\Delta x_i} \quad (3.2)$$

This represents the average of the output parameters (runoff or soil loss) for every level of the input parameter under analysis minus the output at the specific level of input parameter divided by the number of iterations. The overall elementary effect for a parameter is the average of all of these values for each iteration (Saltelli et al., 2009). Calibration will be completed using the parameters identified as sensitive for each output.

Using APEX_CUTE, the sensitive parameters can be selected, as well as the time step desired. For calibration of runoff, daily observed runoff data is available so calibration is completed on a daily time step. Using 2000 iterations for the analysis of each individual parameter, the best combination of parameters with respect to PBIAS, Nash-Sutcliffe, and R^2 are identified and used in the model. This process is repeated for sensitive parameters for soil loss and for each of the three management practice models. Manual calibration was completed for parameters that are not included in APEX_CUTE and consists of a trial and error approach to identify the best representation of the parameter. Parameters included in the manual calibration include the land use number for each operation which governs the CN. For crop yield, the potential heat units were manually calibrated and were the only parameters altered for crop growth. Some soils characteristics were manually calibrated for runoff and soil loss and the estimation method used for soil loss and runoff were manually calibrated. The remaining calibrated parameters for soil loss and runoff are included in Table 3.5 and Table 3.6.

Table 3.5 Calibrated Parameters for Runoff

Parameter	Definition	Range
1	Crop canopy-PET	1-2
12	Soil evaporation coefficient	1.5-2.5
15	Runoff CN Residue Adjustment Parameter	0.0-0.3
16	Expands CN retention parameter	1.0-1.5
17	Soil evaporation-plant cover factor	0.0-0.5
20	Runoff CN initial abstraction	0.05-0.4
25	Exponential coefficient for rainfall intensity on curve number	0.0-2.0
29	Biological mixing efficiency	0.1-0.5
34	Hargreaves PET equation exponent	0.5-0.6
40	Groundwater storage threshold	0.001-1
42	SCS CN index coefficient	0.3-2.5
49	Maximum rainfall interception by plant canopy	0.0-15.0
50	Rainfall interception coefficient	0.05-0.3
90	Subsurface flow factor	1.0-100
FC	Field Capacity	0.1-0.6
UW	Wilting Point	0.01-0.5
BD	Bulk Density	0.5-2.5
APM	Peak runoff rate	0-1
INFL	Runoff Estimation Methodology	n/a
IET	Potential Evapotranspiration Code	n/a
LUN	Land Use Number	n/a

Table 3.6 Calibrated Parameters for Sediment Yield

Parameter	Definition	Range
2	Root growth-soil strength	1-2
5	Soil water lower limit	0-1
13	Wind erodibility coefficient	0-3
19	Sediment Routing coefficient (t/m^3)	0.01-0.05
29	Biological mixing efficiency	0.1-0.5
33	Coefficient in MUST EQ	2.0-3.0
78	Soil water value to delay tillage	0-1
PEC	Erosion control practice factor	0.1-0.9
SATC	Saturated conductivity (mm/h)	0.00001-100
DRV	Equation for Water Erosion	n/a

3.4 Model Evaluation

The Nash-Sutcliffe efficiency (NSE) calculated for the calibrated values represents the variance of the simulated data from the observed data. It tests the fit of the simulated versus observed data to a 1:1 line. With an NSE value greater than 0, the simulated data is a better prediction than the mean observed value. NSE is calculated as follows and will be calculated for this study using the Web-based Hydrograph Analysis Tool (Moriasi, et al., 2007).

$$NSE = \frac{\sum_{i=1}^{n}\left(Y_i^{obs}-Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs}-Y^{mean}\right)^2} \qquad (3.3)$$

Percent bias (PBIAS) is calculated to understand the under or overestimation of the simulated values. A value less than 0 concludes that the model has overestimated the parameter. PBIAS is calculated using the formula below (Moriasi, et al., 2007).

$$PBIAS = \left(\frac{\sum_{i=1}^{n}\left(Y_i^{obs}-Y_i^{sim}\right)*100}{\sum_{i=1}^{n}Y_i^{obs}}\right) \qquad (3.4)$$

According to Moriasi et al. (2007), monthly NSE values greater than 0.5 show satisfactory results for every response of interest. Likewise, monthly PBIAS values less than 25% for runoff prediction and less than 55% for monthly sediment prediction are acceptable (Moriasi, et al., 2007). Other criteria has been used to evaluate daily model performance, including $R^2 > 0.5$ and NSE > 0.30 for runoff, sediment, and crop yield and PBIAS less than 35% for runoff and 60% for sediment (Bhandari et al., 2016, Ramirez et al., 2017). While this and other criteria is not defined as an official guideline, these values have been used in similar studies and will be followed when determining the accuracy of this model prediction for runoff, sediment, and crop yield (Ramirez et al., 2017). A summary of the acceptable ranges is shown in Table 3.7.

Table 3.7 Criteria for Difference Measurements

<table>
<tr><th rowspan="2">Event Scale</th><th rowspan="2">Measure</th><th colspan="2">Satisfactory Range</th></tr>
<tr><th>Runoff</th><th>Sediment</th></tr>
<tr><td rowspan="3">Daily (Ramirez-Avila et al., 2017)</td><td>NSE</td><td>> 0.3</td><td>> 0.3</td></tr>
<tr><td>R^2</td><td>> 0.5</td><td>> 0.5</td></tr>
<tr><td>PBIAS</td><td>< 30%</td><td>< 60%</td></tr>
<tr><td rowspan="3">Monthly (Moriasi et al., 2007)</td><td>NSE</td><td>> 0.5</td><td>> 0.5</td></tr>
<tr><td>R^2</td><td>> 0.5</td><td>> 0.5</td></tr>
<tr><td>PBIAS</td><td>< 25%</td><td>< 55%</td></tr>
</table>

The Mann-Whitney test is used to detect significant differences between two groups, such as observed and predicted data. It does not require that normal distributions are assumed and therefore can be used on the hydrological data of this study. The test results in a p-value that can be compared to the p-value for 95% confidence to determine the acceptance or rejection of the null hypothesis that the values are not significantly different. The statistical measures will be evaluated for daily, monthly, and annual predictions for runoff and soil loss, while crop yield can only be evaluated annually.

When the models for each management practice are calibrated and validated for the most accurate projection of the expected runoff, crop yield, and soil loss, analysis can begin. This analysis includes the comparisons of rainfall and runoff for each management practice to understand the environmental and economic implications of each scenario.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Calibrated Values

The calibration was completed to determine the values of the sensitive model parameters that best represent the different management practices. These values are included in the model to most accurately represent runoff, soil loss, and crop yield. The final values for each parameter and each management practice are included in Tables 4.1-4.3. The potential heat units were consistent across the different management practices, with minor variations, especially those associated with rice growth. In general, increasing potential heat units resulted in increased crop yield, until a certain threshold was reached, and crop yield began decreasing. In many cases, the optimal potential heat unit was the threshold value, maximizing the predicted crop yield to match the observed yield. Calibrated values for parameters affecting runoff that changed significantly between management practices include the parameters relating to the CN estimation. The initial abstraction ratio, the exponential coefficient for rainfall intensity, and the CN index coefficient varied across the management practices, with higher values for conventional tillage resulting in the expected increased runoff. Most values for the calibrated parameters affecting soil loss are consistent across the different management practices. The model was extremely over predicting the erosion under conventional tillage; therefore, the erosion control practice factor was higher under conventional tillage to help the model more accurately represent the conditions. One possible reason for the overestimation of sediment is errors in the collection of the data. Only monthly sediment values are available for comparison so certain days with inaccurate readings or days that may have been skipped are not available. The actual rainfall distribution might not be reflected accurately in the model, using the Modified Universal Soil Loss Equation.

Table 4.1 Calibrated Parameters for Crop Yield

Crop Yield						
				Conventional Tillage	Reduced Tillage	Direct Planting
Crop	Parameter	Definition	Year	Calibrated Value		
Soy	PHU	Potential Heat Units	1996	1300	1300	1300
			1997	1200	975	1150
			1998	750	525	750
			1999	1500	1500	1500
Rice	PHU	Potential Heat Units	1996	-	-	-
			1997	1000	850	500
			1998	-	-	-
			1999	775	755	525
Corn	PHU	Potential Heat Units	1996	-	-	-
			1997	-	-	-
			1998	500	425	350
			1999	-	-	-

Table 4.2 Calibrated Parameters for Runoff

		Conventional Tillage	Reduced Tillage	Direct Planting
Parameter	Definition	Calibrated Value		
1	Crop canopy-PET	1.5	1.5	1.5
12	Soil evaporation coefficient	1.647	1.5	2.5
15	Runoff CN Residue Adjustment Parameter	0	0.008	0.008
16	Expands CN retention parameter	1	1.489	1.5
17	Soil evaporation-plant cover factor	0.22	0.5	0.5
20	Runoff CN initial abstraction	0.265	0.05	0.4
25	Exponential coefficient for rainfall intensity on curve number	0.7	0.14	1.991
29	Biological mixing efficiency	0.1	0.5	0.3
34	Hargreaves PET equation exponent	0.57	0.591	0.552
40	Groundwater storage threshold	0.737	0.99	0.998
42	SCS CN index coefficient	2.5	0.3	1.8
49	Maximum rainfall interception by plant canopy	15	15	12.098
50	Rainfall interception coefficient	0.26	0.3	0.29
90	Subsurface flow factor	2	2	1
FC	Field Capacity	0.3	0.28	0.26
UW	Wilting Point	0.17	0.17	0.17
BD	Bulk Density	1.3	2.5	1.9
APM	Peak runoff rate	0.3	0.56	0.6
INFL	Runoff Estimation Methodology	CN estimate of Q	CN estimate of Q	CN estimate of Q
IET	Potential Evapotranspiration Code	Hargreaves	Hargreaves	Hargreaves

Table 4.2 (continued)

LUN	Land Use Number-crop growth	13	13	24
CN	Curve Number-crop growth	59	59	25
LUN	Land Use Number-fallow	1	1	1
CN	Curve Number- fallow	77	77	77

Table 4.3 Calibrated Parameters for Sediment Yield

Sediment				
		Conventional Tillage	Reduced Tillage	Direct Planting
Parameter	Definition	Calibrated Value		
2	Root growth-soil strength	1.875	2	2
5	Soil water lower limit	0.307	1	0.004
13	Wind erodibility coefficient	1	2	2
19	Sediment Routing coefficient (t/m^3)	0.003	0.003	0.01
29	Biological mixing efficiency	0.1	0.5	0.3
33	Coefficient in MUST EQ	2	3	2.7
78	Soil water value to delay tillage	1	0.988	0.988
PEC	Erosion control practice factor	0.7	0.08	0.38
SATC	Saturated conductivity (mm/h)	20.8	90	100
DRV	Equation for Water Erosion	MUST	MUST	MUST

4.2 Runoff Results

The runoff estimation from the model is an important parameter to consider when comparing the management practices for the environmental impacts of each. The runoff results are related to the climate and soil conditions and should show consistent relationships. For the tropical soils in the study area, no tillage practices are expected to be the most beneficial to the soil properties, including higher surface soil coverage, hydraulic conductivity, and aggregation (Busari et al., 2015). These properties have been found to help reduce runoff under no tillage or minimum tillage practices (Bhatt and Khera, 2006). Therefore, the management with no tillage is expected to produce the least runoff while conventional is expected to produce the highest. Below are the results for each management practice. The measured and simulated values of runoff from each management scenario are compared to show the variability and the compliance with statistical recommendations.

4.2.1 Conventional Tillage

Following calibration, the results for daily runoff prediction are satisfactory according to the statistical criteria outlined by Ramirez et al. (2017) (NSE > 0.3, PBIAS < 30% and $R^2 > 0.5$). The model slightly overpredicted the daily runoff values, with an NSE of 0.50 and an R^2 value of 0.55. The daily PBIAS value was -51.91%, which is above the recommended acceptable value for accurate prediction. This represents an overestimation, which is mostly identified in the early study periods of the model. The Mann-Whitney test was conducted to determine a daily p-value of 0.06. This is greater than 0.05, allowing acceptance of the null hypothesis that the difference between the observed and predicted runoff values is not significantly different than 0 at 95% confidence. The monthly NSE and R^2 values for runoff are within the accepted standards outlined by Moriasi et al. (2007), while the annual NSE is below the acceptable standards, showing overestimation. The monthly p-value determined by the Mann-Whitney test is 0.31, also allowing the acceptance of the null hypothesis. The observed mean daily runoff was 1.14 mm with a standard deviation of 6.54 mm and the predicted mean daily runoff was 1.74 mm with a standard deviation of 6.24 mm. Table 4.4 below shows a summary of the statistical values.

Table 4.4 Statistics for Runoff Under Conventional Tillage

	Observed		Predicted		NSE	R^2	PBIAS	p-value
	Mean	SD	Mean	SD				
Daily	1.14	6.54	1.74	6.24	0.502	0.554	-51.91	0.057
Monthly	28.37	37.56	43.24	42.16	0.570	0.783	-52.39	0.305
Annual	134.39	59.42	209.92	79.79	-1.12	0.732	-56.20	0.312

When graphically comparing the observed and predicted daily and monthly runoff, a consistent trend is observed for the daily values. The daily and monthly observed and predicted values are graphed against each other in Figures 4.1 and 4.2 and are compared to the 1:1 line. There is some scatter in the larger values and for some days, the model predicts runoff when there is none recorded. This occurs under every tillage practice and can be seen for conventional tillage in Figure 4.1. This could be due to the hydrologic characteristics of the soil not being properly simulated by APEX, especially at the beginning of the rainy period, as many of the occurrences were observed during this period from April to July. The soil was drier than usual in this time period because of the lack of rain in the prior months. The soil retained more water during the initial events and had less runoff that may be overpredicted given the direct association of the CN method to a rainfall depth (Zema et al., 2012). The daily CN in APEX could have been overpredicted by the model generating a hydrologic response at smaller rainfall depths. There were also cases in which there was observed runoff but the model predicted none. This occurred less frequently than the previous condition and are all following large rain events (over 20 mm) in June, July, and August, towards the end of the rainy season. Several other studies also found several instances of zero simulated runoff generated by larger storms in hydrologic models (Zema et al., 2012, Licciardello et al., 2007). Because the error occurs in higher rainfall, it is unlikely that it is an error in the sampled data. Zema et al. (2012) suggested the model may have under predicted the daily CN value to compensate for the rainfall, causing no runoff to be predicted for that event.

Total monthly and annual data comparison are shown below in Figures 4.3 and 4.4. The runoff values are also compared to the observed precipitation for the study period and strong trends are shown. Table 4.5 shows the annual runoff as a percentage of annual rainfall. For the conventional tillage model, a warming period was added in 1995 with pasture. This helped reduce the model over prediction that was first observed for 1996 and allowed for better trends in the early periods of the study (1996 and the beginning of 1997). The predicted runoff was higher during the first half of each year when rice and corn were planted. The precipitation was higher during these periods as well.

Table 4.5 Predicted and Observed Runoff as Percentage of Precipitation Under Conventional Tillage

Year	Precipitation (mm)	Predicted	Observed
1996	440.20	0.23	0.23
1997	894.67	0.23	0.12
1998	769.80	0.26	0.12
1999	1394.62	0.23	0.17

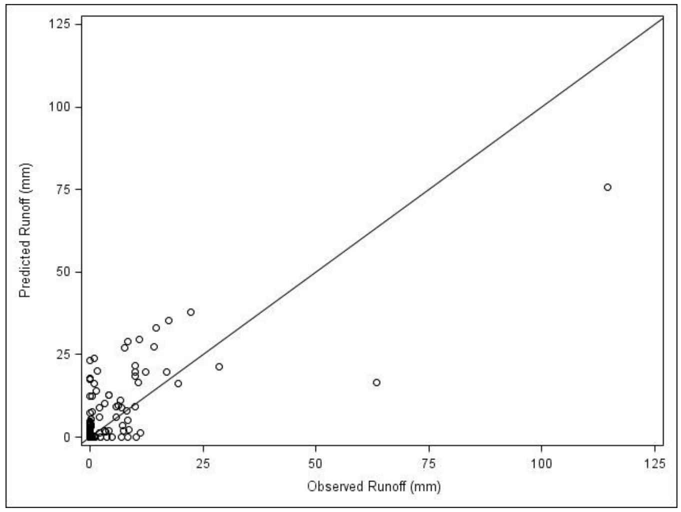

Figure 4.1 Observed vs. Predicted Daily Runoff under Conventional Tillage

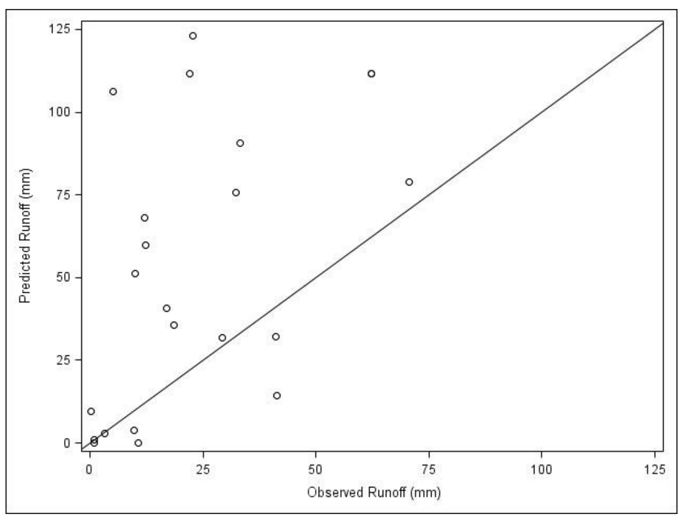

Figure 4.2 Observed vs. Predicted Monthly Runoff Under Conventional Tillage

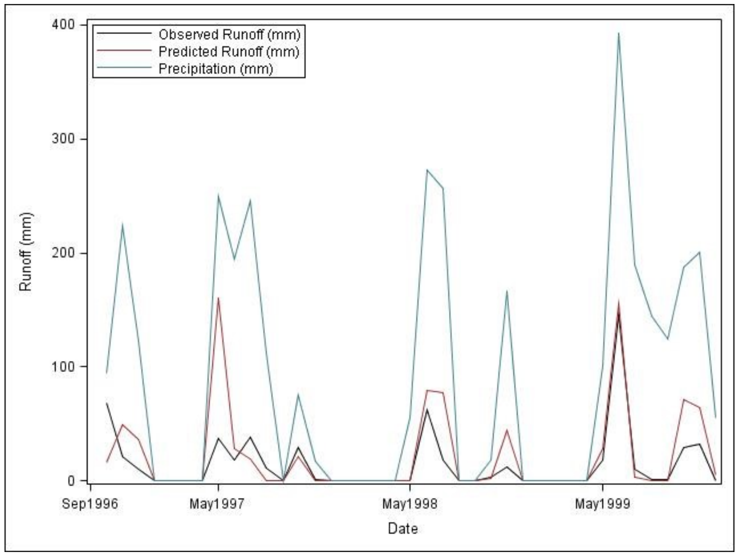

Figure 4.3 Monthly Comparison of Runoff Under Conventional Tillage

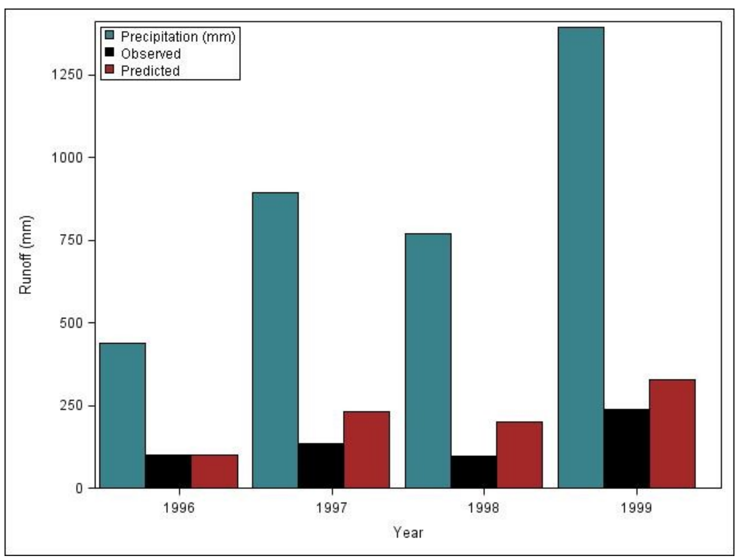

Figure 4.4 Annual Comparison of Runoff Under Conventional Tillage

4.2.2 Reduced Tillage

Following calibration, the results for runoff prediction were satisfactory according to the statistical criteria from Ramirez et. al. (2017), and Moriasi et. al. (2007), outlined above. For daily prediction, the observed NSE value was 0.70 and the R^2 value was 0.71. The monthly and annual data were also within the accepted criteria for NSE and R^2 values, all greater than 0.7. The daily PBIAS value is -21.73%, which is within the recommended acceptable value for accurate prediction of 30% and 25% for daily and monthly simulations, and shows a small overestimation in runoff. The observed mean daily runoff is 1.78 mm with a standard deviation of 9.40 mm and the predicted mean daily runoff is 2.16 mm with a standard deviation of 8.91 mm. The daily Mann-Whitney p-value is 0.055, accepting the null hypothesis and showing insignificant difference between the observed and predicted daily values at the 95% confidence level. Table 4.5 below shows a summary of the statistical values.

When graphically comparing the observed and predicted daily and monthly runoff values, a good concordance between observed and predicted values was observed. The daily and monthly observed and predicted data were compared in Figure 4.5 and 4.6 and shown against the 1:1 line. The statistical values shown in Table 4.6 evidence correlation and accurate prediction of the measured data. The overall monthly data comparison is shown below in Figure 4.7 and the annual comparison in Figure 4.8. The observed and predicted runoff values are compared to the precipitation and a relatively strong relationship was evidenced. Table 4.7 shows the annual runoff as a percentage of annual rainfall. In 1997 and 1998, the runoff is higher in the first half of the year, when rice and corn are planted and when precipitation is higher. In 1999, the runoff from both the first and second half of the year is higher than the other years, as precipitation was also higher during this time.

Table 4.6 Statistics for Runoff Under Reduced Tillage

	Observed		Predicted		NSE	R^2	PBIAS	p-value
	Mean (mm)	SD	Mean (mm)	SD				
Daily	1.78	9.4	2.16	8.91	0.696	0.709	-21.73	0.055
Monthly	28.56	55.89	80.3	322.64	0.809	0.833	-20.90	0.538
Annual	230.81	194.08	280.97	157.26	0.742	0.843	-21.73	0.665

Table 4.7 Predicted and Observed Runoff as Percentage of Precipitation Under Reduced Tillage

Year	Precipitation (mm)	Predicted	Observed
1996	497.50	0.38	0.16
1997	1003.27	0.16	0.20
1998	881.00	0.30	0.15
1999	1532.02	0.33	0.33

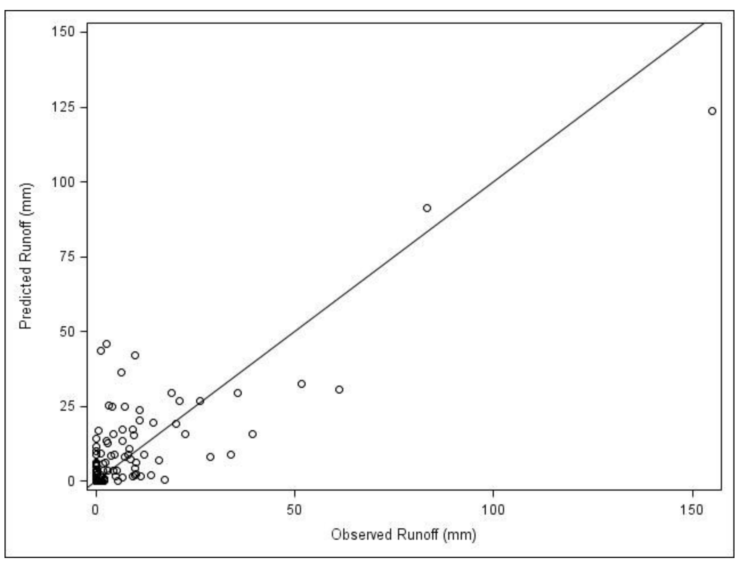

Figure 4.5 Observed vs. Predicted Daily Runoff Under Reduced Tillage

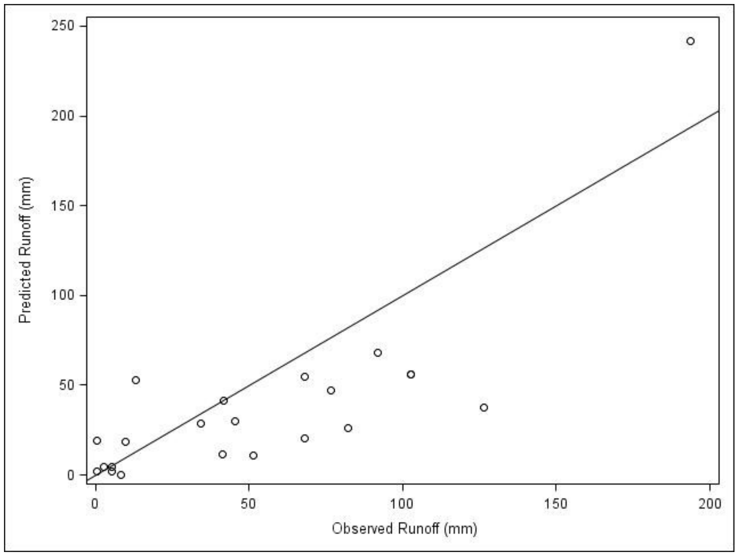

Figure 4.6 Observed vs. Predicted Monthly Runoff Under Reduced Tillage

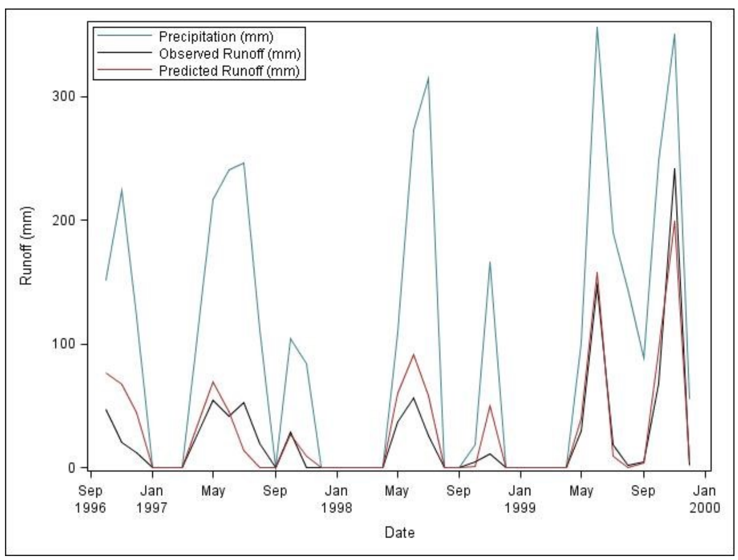

Figure 4.7 Monthly Comparison of Runoff Under Reduced Tillage

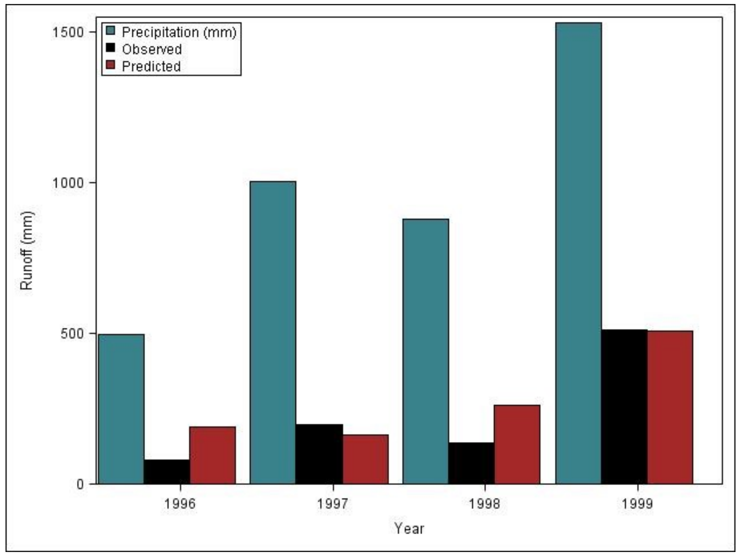

Figure 4.8 Annual Comparison of Runoff Under Reduced Tillage

4.2.3 No Tillage/Direct Planting

Following calibration, satisfactory statistical results were achieved according to the criteria outlined by Ramirez-Avila et al. (2017) and Moriasi et al. (2017). The daily NSE value was 0.547 and the R^2 for daily runoff was 0.647. The daily PBIAS was -18.10%, which is below the recommended 30% and 25%, showing satisfactory results. The negative value represents and over estimation of the modeled parameter; however, the percentage was small and the overestimation was not significant. The monthly and annual NSE and R^2 values were also within the acceptable parameters outlined above. The annual prediction showed the strongest correlation, meaning that overall, the runoff, specially the monthly and annual predictions were accurately represented by the model. The predicted mean daily runoff was 1.22 mm with a standard deviation of 6.23 mm and the observed mean daily runoff was 1.03 mm. The Mann-Whitney p-value to compare daily values was 0.31 and leads to the acceptance of the null hypothesis at the 95% confidence level, showing no significant difference between the observed and predicted daily values. Table 4.8 below shows a summary of the statistical values.

The graphical representation of predicted and observed daily, monthly, and annual runoff values support the statistics representing accurate estimation of the runoff data. In Figures 4.9 and 4.10, the observed versus predicted daily and monthly runoff are compared to the 1:1 line show a linear trend in the data. Because lower runoff is expected under direct planting, there are several zero values for predicted runoff. In addition to the abobve mentioned consideration of the underestimation of daily CN values due to a balance with overestimated evapotranspiration, it could also be related to the fact that the initial abstraction parameter (□), which is fundamental in the estimation of the runoff depth, remains constant during the entire period of evaluation not considering potential effects of seasonality. The monthly comparison in Figure 4.11 shows strong correlation between predicted and observed values. The runoff values are also compared to the monthly rainfall and the monthly predicted and observed runoff follow the same trend as precipitation, as expected. Higher rainfall and runoff were observed in 1999, with very low runoff in 1998. In general, the first half of each year shows slightly higher runoff because of higher precipitation occurring in the first part of the year. The annual comparison in Figure 4.12 also represented the low runoff observed in 1998 and Table 4.9 shows the annual runoff as a percentage of annual rainfall, also showing this low annual value.

Table 4.8 Statistics for Runoff Under Direct Planting

	Observed		Predicted		NSE	R^2	PBIAS	p-value
	Mean	SD	Mean	SD				
Daily	1.03	5.57	1.22	6.23	0.547	0.647	-18.10	0.311
Monthly	12.96	26.06	15.52	33.1	0.622	0.822	-31.32	0.720
Annual	126.33	108.5	151.32	109.99	0.746	0.827	-18.10	0.665

Table 4.9 Predicted and Observed Runoff as Percentage of Precipitation Under Direct Planting

Year	Precipitation (mm)	Predicted	Observed
1996	497.50	0.35	0.16
1997	919.64	0.10	0.08
1998	985.30	0.05	0.06
1999	1509.52	0.20	0.19

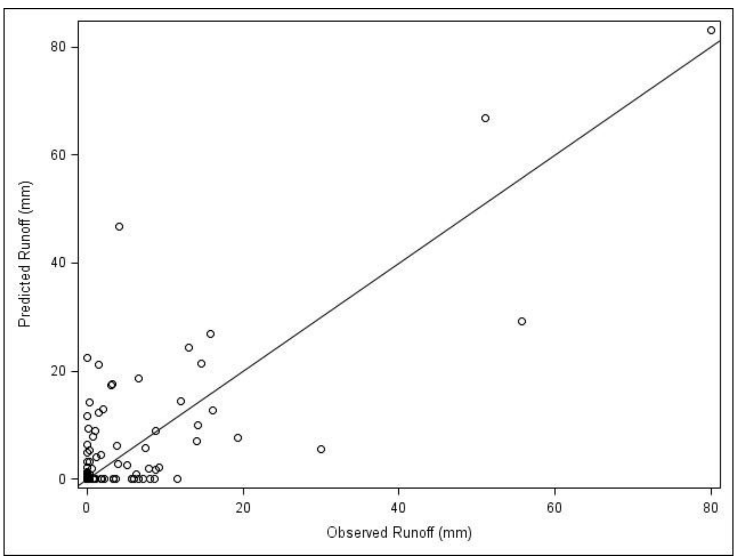

Figure 4.9 Observed vs. Predicted Daily Runoff Under Direct Planting

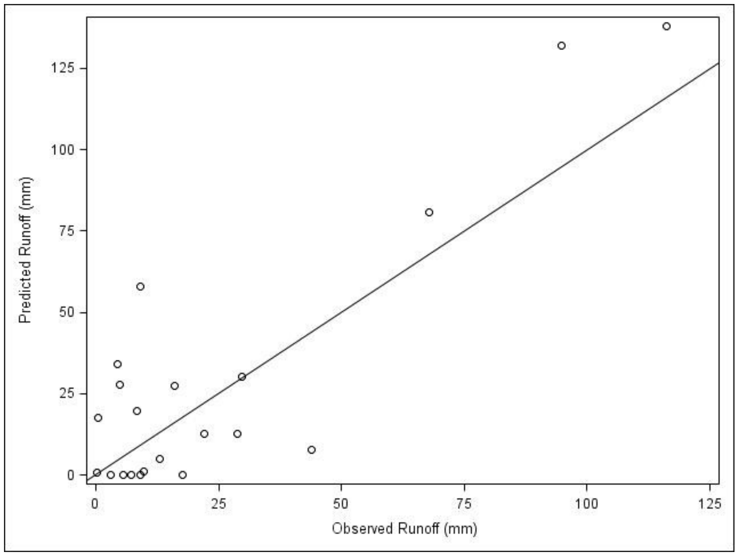

Figure 4.10 Observed vs. Predicted Monthly Runoff Under Direct Planting

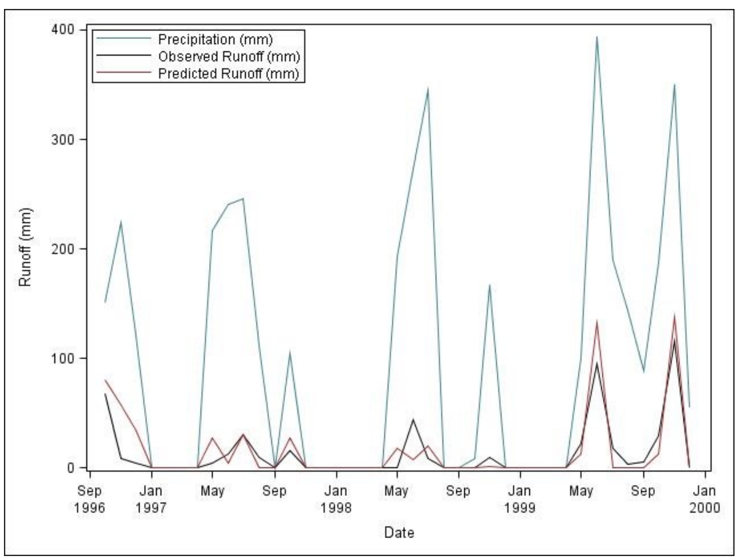

Figure 4.11 Monthly Comparison of Runoff Under Direct Planting

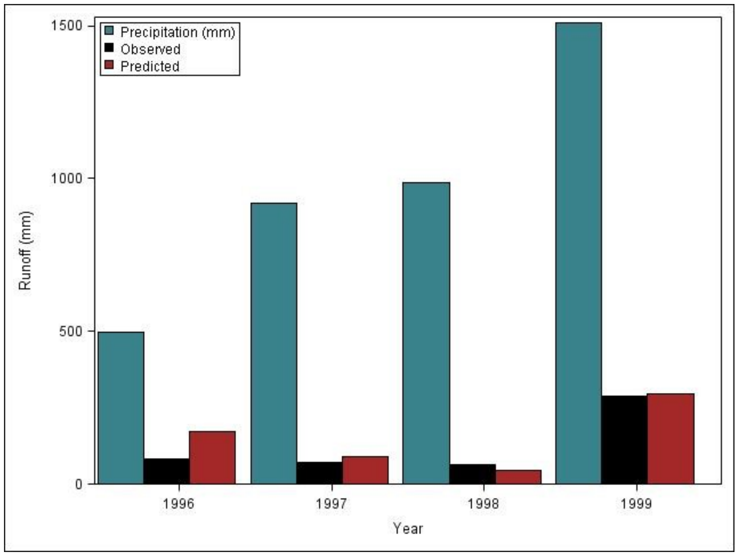

Figure 4.12 Annual Comparison of Runoff Under Direct Planting

4.3 Sediment

The sediment yield from each field under different management practices was collected by researchers at CORPOICA and were modeled to better understand the effects of different tillage practices on the amount of soil loss from each field. As discussed above, soil loss is important to understand as it relates to soil degradation and changes in productivity. The results from each management practices are outlined below and further discussion is provided.

4.3.1 Conventional Tillage

Monthly observed data for sediment yield was available for calibration and comparison to the modeling results. This monthly data was further broken down to annual sediment yield and sediment yield by crop cycle (including the two periods of every year when crop rotation occurred). The monthly NSE and R^2 values under conventional tillage were not within the acceptable values for modeling sediment. The monthly NSE is -1.114 and the R^2 is 0.302. However, the PBIAS value was 18.03%, showing some under prediction but limited variation. The monthly p-value determined with the Mann-Whitney test was 0.141, showing insignificant difference between the observed and predicted monthly values with 95% confidence. The poor NSE value could be a result of combined problems related to the collected data and the already reported problems in APEX to predict soil erosion. Several variations were found in the measured data, such as extremely low values for certain months that had large runoff and expected high sediment yields. When comparing annual and biannual sediment yield values, the NSE values were 0.513 and 0.721, respectively, with R^2 values of 0.649 and 0.792. This shows that more generally, the overall predictions are representative of the observed data. While each separate month was not showing accurate predictions, the entire year and the overall biannual well represented sediment yield. The mean observed monthly sediment yield was 0.59 Mg/ha with a standard deviation of 0.68 Mg/ha and the mean predicted is 0.49 Mg/ha with a standard deviation of 1.18 Mg/ha. Table 4.10 shows a summary of the statistics.

The graphical representation of the sediment yield model highlights some of the inconsistencies identified in the statistics. The comparison of observed and predicted monthly sediment yield shown in Figure 4.13 evidenced some agreement for smaller values, and higher variation as the sediment yield increases. Monthly comparisons are shown in Figure 4.14 and the comparison based on biannual and annually shown in Figures 4.15 and 4.16An important factor to consider, APEX predicts erosion based on a subroutine and model derived from the USLE equation, which was originally developed to estimate annual erosion rates. Although the different USLE derived equations in APEX have been adapted to estimate daily soil loss, it could be importantly misestimated as the determination of variables such as the cover factor (C) and the erosivity factor (R) could not be properly representing the changes observed in the field. Another fact for consideration, USLE was intended to guide on the determination of erosion rates in the United States. Ramirez et al. (2001) evidenced that the USLE equation did not properly represent annual erosion rates for the same studied plots, and found the energy of the rainfall estimated by the USLE procedure could be misrepresenting the conditions for the area of study.

Table 4.10 Statistics for Sediment Yield Under Conventional Tillage

	Observed		Predicted		NSE	R^2	PBIAS	p-value
	Mean (Mg/ha)	SD	Mean (Mg/ha)	SD				
Monthly	0.59	0.68	0.49	1.18	-1.114	0.302	18.03	0.141
Biannual	1.52	1.68	1.25	1.83	0.721	0.792	18.03	0.371
Annual	2.67	2.14	2.19	2.29	0.513	0.649	18.03	0.665

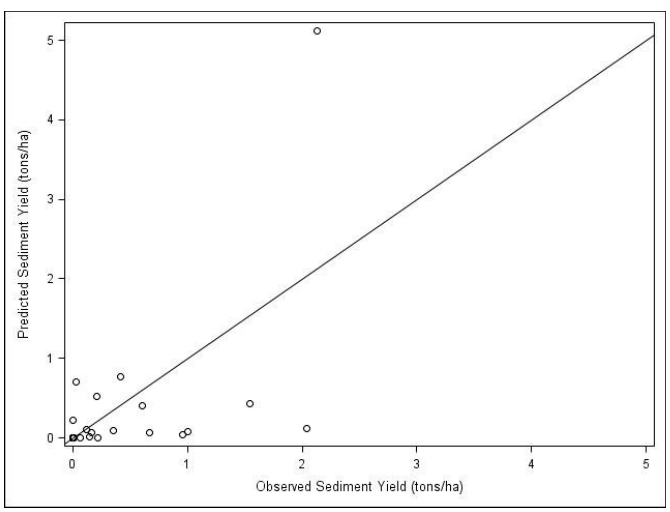

Figure 4.13 Observed vs. Predicted Sediment Yield Under Conventional Tillage

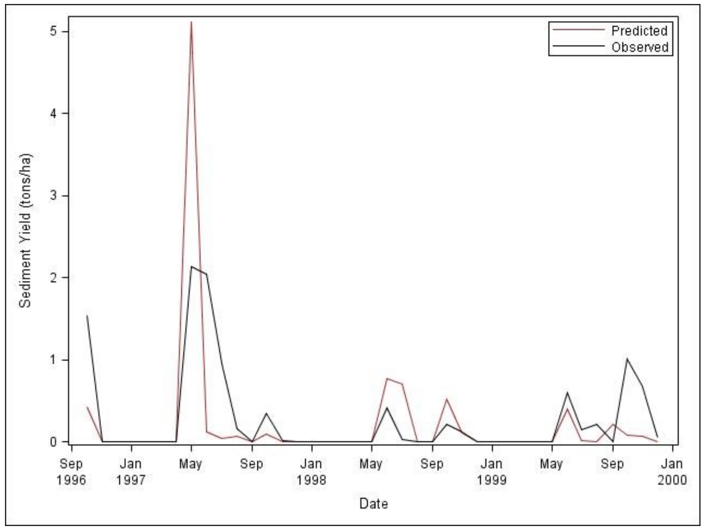

Figure 4.14 Monthly Comparison of Sediment Yield Under Conventional Tillage

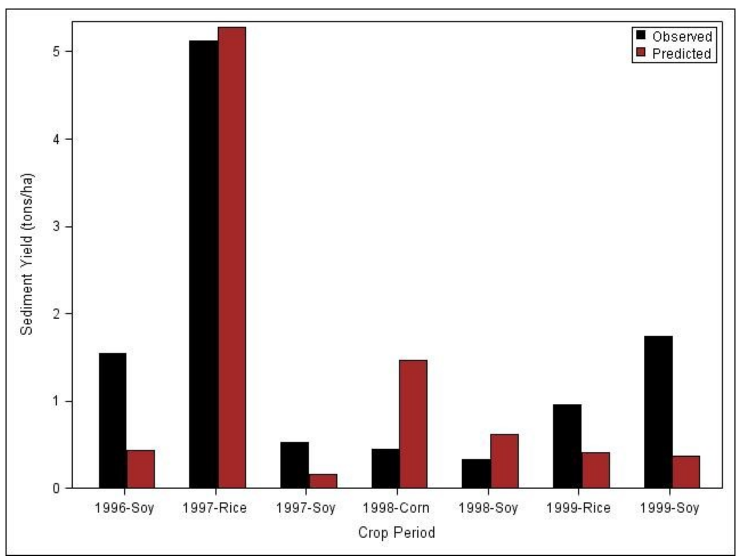

Figure 4.15 Biannual Comparison of Sediment Yield Under Conventional Tillage

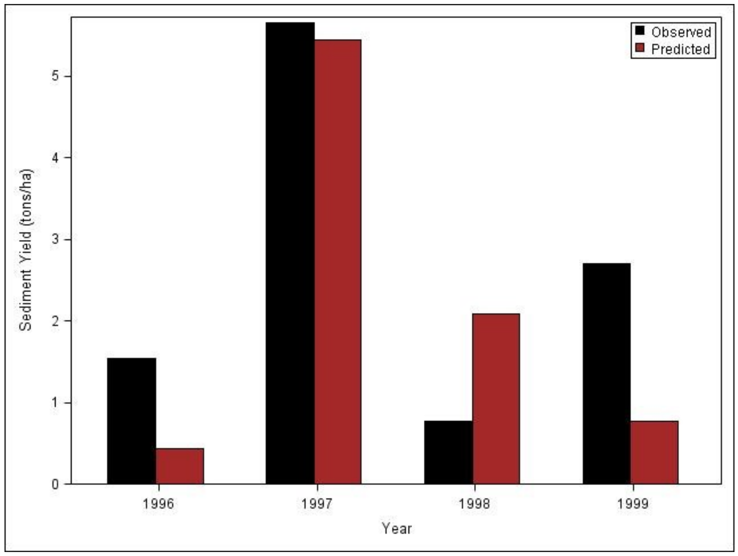

Figure 4.16 Annual Comparison of Sediment Yield Under Conventional Tillage

4.3.2 Reduced Tillage

Using the monthly, biannual, and annual values for observed and predicted sediment yield, similar results were observed under reduced tillage to conventional tillage. The monthly NSE value was unsatisfactory at -0.522 with a R^2 value of 0.137. The PBIAS was 20.62%, which is considered acceptable and showed slight underestimation and little variation. The monthly Mann-Whitney p-value was 0.438, allowing acceptance of the null hypothesis that the observed and predicted monthly values are not significantly different. As with conventional tillage, there were some discrepancies in the observed data, specifically in 1998, a period affected by the El Niño–Southern Oscillation (ENSO), which significantly reduced the amount of precipitation during that year. In addition, several dates in May and June of 1998 were missing data. While the monthly NSE and R^2 values are not acceptable, the annual and biannual comparisons showed better overall prediction. The annual NSE was 0.438 with an R^2 of 0.640 and the biannual NSE was 0.566 with an R^2 of 0.649. This showed acceptable overall prediction for the longer time periods. The mean observed monthly sediment yield was 0.7 Mg/ha and the mean predicted monthly sediment yield was 0.56 Mg/ha, with a standard deviation of 0.6 and 0.69 Mg/ha respectively. Table 4.11 shows a summary of the statistics.

The comparison of monthly observed versus predicted sediment yield in Figure 4.17 showed a better agreement under reduced tillage. The graphical comparison of the monthly observed and predicted sediment data is presented in Figure 4.18. Likewise, Figures 4.19 and 4.20 show biannual and annual comparison and are more consistent with the observed data. This shows that while individual months are not always accurately predicting the sediment yield, the overall values for each year or crop period are better consistent and can be used to represent the system. It verifies the statement before presented that relates the valid use of USLE or derived equations for time scales smaller than annual.

Table 4.11 Statistics for Sediment Yield Under Reduced Tillage

	Observed		Predicted		NSE	R^2	PBIAS	p-value
	Mean (Mg/ha)	SD	Mean (Mg/ha)	SD				
Monthly	0.7	0.6	0.56	0.69	-0.520	0.141	20.62	0.438
Biannual	1.81	1.63	1.44	1.07	0.566	0.649	20.62	1.00
Annual	3.16	1.95	2.51	1.1	0.474	0.65	20.62	0.470

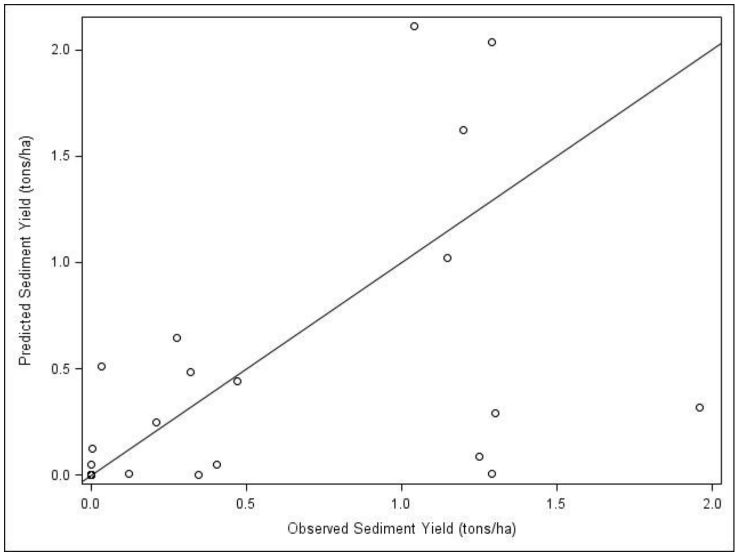

Figure 4.17 Observed vs. Predicted Sediment Yield Under Reduced Tillage

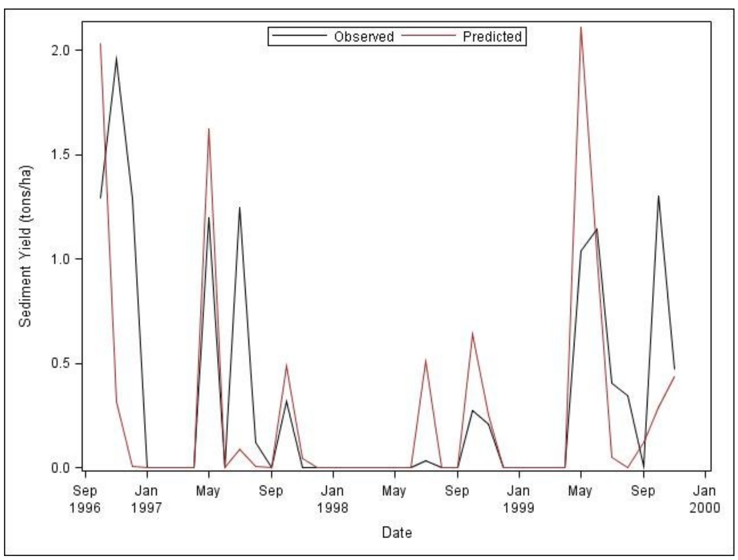

Figure 4.18 Monthly Comparison of Sediment Yield Under Reduced Tillage

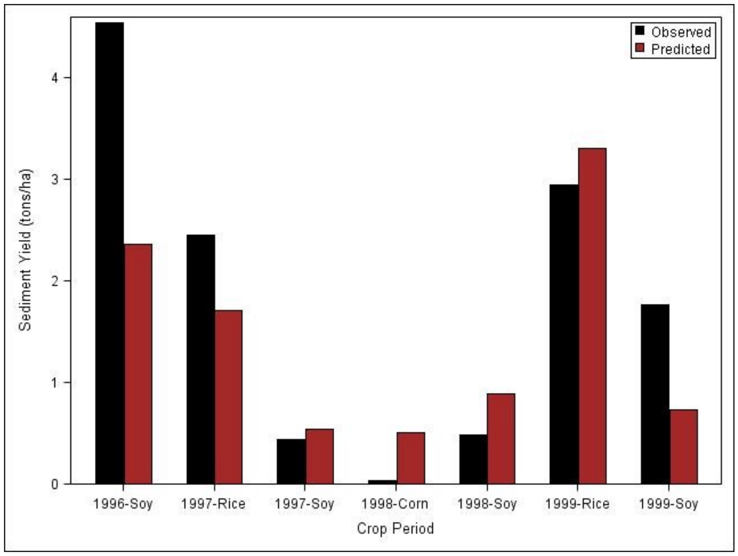

Figure 4.19 Biannual Comparison of Sediment Yield Under Reduced Tillage

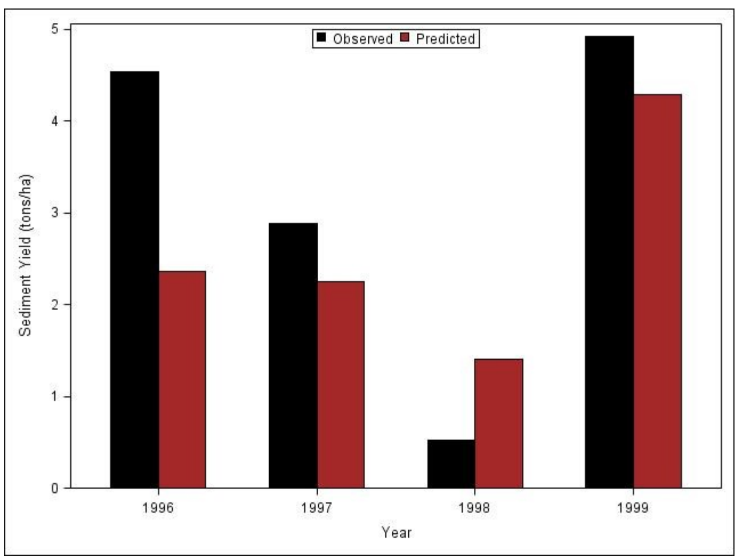

Figure 4.20 Annual Comparison of Sediment Yield Under Reduced Tillage

4.3.3 No Tillage

Despite the better agreement, as with conventional and reduced tillage, the model predictions were not satisfactory. The NSE and R^2 results for sediment yield under no tillage were -0.319 and 0.277, respectively, while the PBIAS was -2.29%, showing slight over prediction with little variation. The graphical representation shown in Figure 4.22 highlights that the predicted and observed values were better related. The p-value for monthly data sets was 0.715, showing no significant difference in the observed and predicted values with 95% confidence. Problems were again discovered with the data from 1998, particularly with values missing from the second half of the year, when soybean was planted. The NSE value for the biannual sediment yield was 0.525 and the R^2 value was 0.561, while the annual values were 0.656 and 0.919, respectively. This shows that the overall prediction of the larger timelines represented the sediment yield more accurately. The mean monthly observed sediment yield was 0.48 Mg/ha while the mean predicted is 0.49 Mg/ha. This similar estimation shows little difference in the means. The remaining statistics are summarized in Table 4.12.

The comparison of monthly observed and predicted sediment data is shown in Figures 4.21and 4.22. The biannual and annual comparisons presented in Figures 4.23 and 4.24 are fairly consistent, with higher overall annual values increasing through the study period. The rotations growing rice showed larger differences in observed and predicted sediment yield. The overall prediction from rice is higher, which leaves more room for error. Rice was also planted at the beginning of the year, when precipitation tends to be higher. Erosion rates were overestimated in 1998, period affected by El Niño, for corn growth, which evidenced the potential effect of a larger estimation of the rainfall energy by the USLE procedure.

Table 4.12 Statistics for Sediment Yield Under Direct Planting

	Observed		Predicted		NSE	R^2	PBIAS	p-value
	Mean (Mg/ha)	SD	Mean (Mg/ha)	SD				
Monthly	0.48	0.42	0.49	0.55	-0.319	0.277	-2.29	0.715
Biannual	1.62	0.83	1.55	0.76	0.525	0.561	-2.29	0.810
Annual	2.28	1.72	2.33	0.77	0.656	0.919	-2.29	0.885

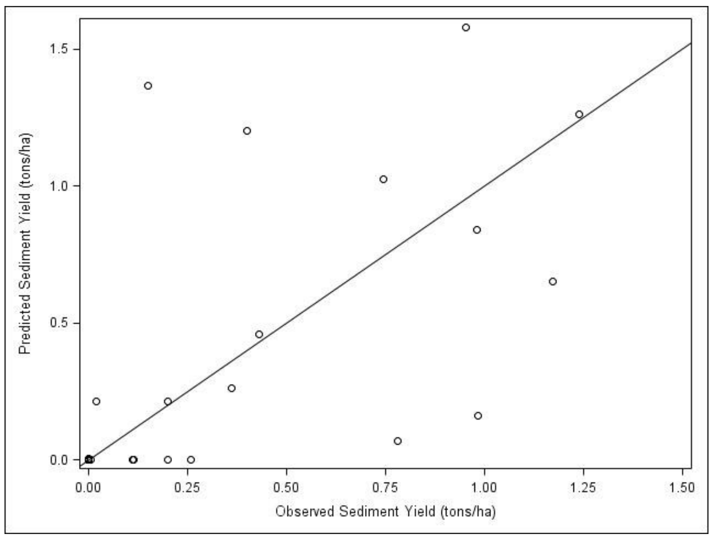

Figure 4.21 Observed vs. Predicted Sediment Yield Under Direct Planting

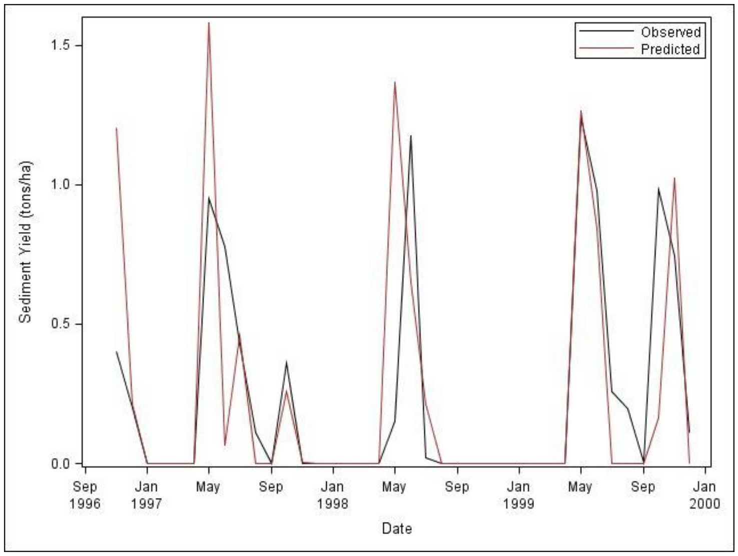

Figure 4.22 Monthly Comparison of Sediment Yield Under Direct Planting

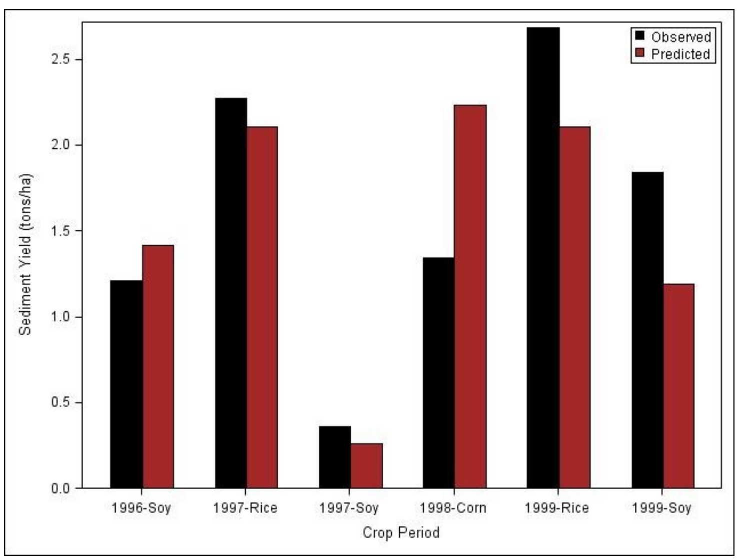

Figure 4.23 Biannual Comparison of Sediment Yield Under Direct Planting

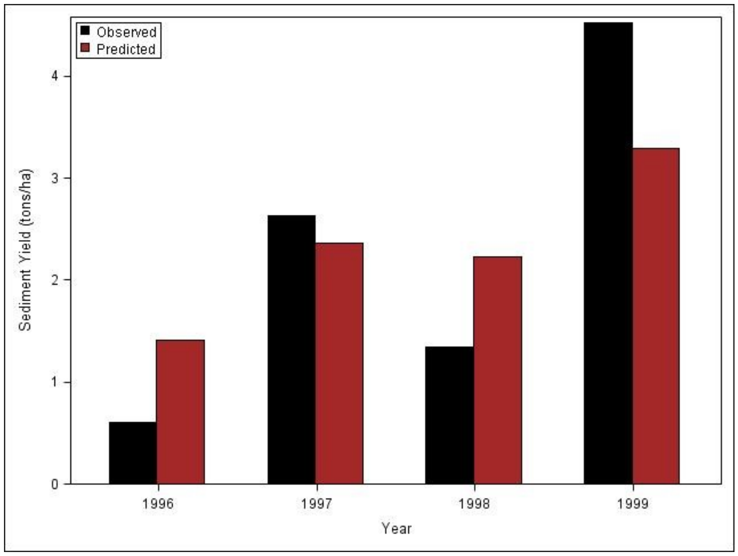

Figure 4.24 Annual Comparison of Sediment Yield Under Direct Planting

4.4 Crop Yield

Annual crop yield data was available for calibration and comparison of the modeled results. Crop yield is the driving force of the economic value of the fields and is related to the soil loss and runoff. It is the most important parameter for farmers and is important to accurately represent for the proper overall calibration of the model.

4.4.1 Conventional Tillage

The crop yield for each crop planted each year of the study produced accurate results. There was no crop data for the soy in 1996; however, all the other crops were represented accurately by the model when compared to the measured values. The NSE value for the crop yield was 0.983 with an R^2 of 0.994. This shows extremely strong representation. The PBIAS was 0.58%, which shows extremely little variation. The p-value for annual comparisons was

0.8831, which represents little variation in the observed and predicted means. The statistics are summarized in Table 4.13.

The graphical representation of the crop yield shown in Figure 4.25 also shows strong correlation. Rice produces the most yield and has the largest discrepancy in 1997 with slight under prediction. However, the model prevailed an accurate representation of the crop yield and is efficient in characterizing the growth characteristics of the plot.

Table 4.13 Statistics for Crop Yield Under Conventional Tillage

	Observed		Predicted		NSE	R^2	PBIAS	p-value
	Mean (Mg/ha)	SD	Mean (Mg/ha)	SD				
Annual	2.01	1.4	2	1.25	0.983	0.994	0.58	0.810
Soy	1.2	0.39	1.3	0.46				
Rice	3.75	0.68	3.54	0.48				
Corn	0.97	-	1.03	-				

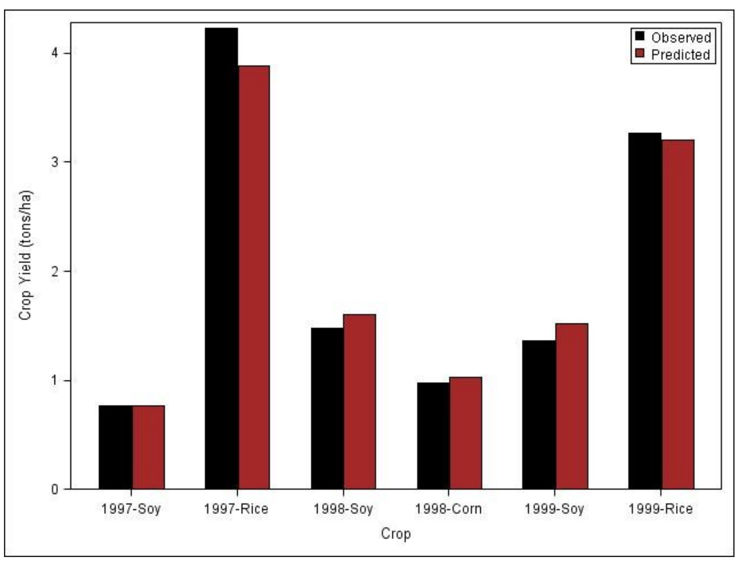

Figure 4.25 Crop Yield Comparison Under Conventional Tillage

4.4.2 Reduced Tillage

As with conventional tillage, there is no yield data available for soy in 1996. The remaining crops in the last three years of the study were accurately represented in the model. The correlation for the yields for each of the planting seasons was strong, with an NSE of 0.819 and an R^2 value of 0.941. The PBIAS was 9.4%, showing very little under prediction. The p-value from the t-test conducted to understand the difference in the means was 0.46. This is higher than the p-value for 95% confidence and therefore the null hypothesis is supported and the difference in the means is not statistically different from zero. The statistics are summarized in Table 4.14.

The graphical representation of the crop yield shown in Figure 4.26 shows strong correlation supporting the statistics. Rice had the most growth and the largest discrepancy among the crops, especially in 1997 with a large under estimation. However, the overall trend was strong, and the crop yield was accurately represented in the model.

Table 4.14 Statistics for Crop Yield Under Reduced Tillage

	Observed		Predicted		NSE	R^2	PBIAS	p-value
	Mean (Mg/ha)	SD	Mean (Mg/ha)	SD				
Annual	2.16	1.55	1.96	1.01	0.819	0.941	9.4	1.00
Soy	1.36	0.69	1.34	0.58				
Rice	3.99	1.01	3.17	0.25				
Corn	0.92	-	1.41	-				

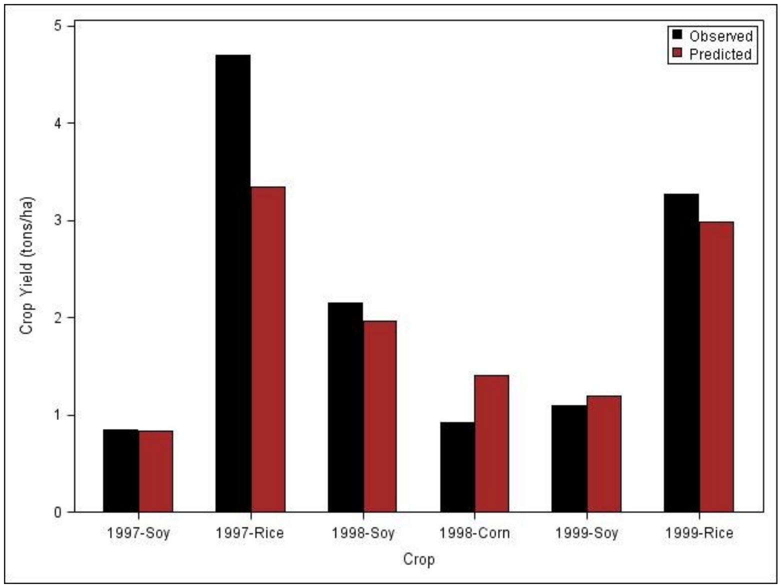

Figure 4.26 Crop Yield Comparison Under Reduced Tillage

4.4.3 No Tillage

The crop yields for each crop for each of the three years with available crop yield data were calibrated for accurate representation of the crop yield data. The correlation was strong, with an NSE of 0.823 and an R^2 of 0.941. The PBIAS was 14.48%, showing some under prediction. However; the results are statistically acceptable and accurately represent the data. The p-value found using the t-test to understand the difference in means was 0.3197, which was larger than the p-value of 0.05 for the 95% confidence interval. This concludes that the difference in the means of the observed and predicted yield are not significantly different than zero. The statistics were summarized in Table 4.15.

The graphical representation of the crop yield in Figure 4.27 supported the strong correlation observed in the statistics. As with conventional tillage and reduced tillage, rice produced the largest yield and had the largest discrepancy in the data, especially in 1997.

However, the results are strongly correlated, and the model can be used to accurately represent crop yield under each management practice.

The fact that rice had the largest difference in agreement between observed and modeled datasets in 1997 can be related to the nature of the database of crop parameters included in APEX. A significant effect on crop yield associated to the water stress is probably expected to occur using the crop variables included in APEX for rice. During the second semester of 1997, El Niño initiated the extended dry period in Colombia. The rice variety used for the study, not available in the APEX database, was very tolerant to dry weather and acid soils, which is reflected in the normal crop yield response observed that semester. Conversely, the crop information from the APEX database was susceptible enough to find that yield reduction during the identified period.

Table 4.15 Statistics for Crop Yield Under Direct Planting

	Observed		Predicted		NSE	R^2	PBIAS	p-value
	Mean (Mg/ha)	SD	Mean (Mg/ha)	SD				
Annual	1.92	1.64	1.64	1.11	0.823	0.941	14.48	0.809
Soy	1.07	0.38	1.08	0.34				
Rice	3.91	1.03	3.03	0.11				
Corn	0.51	-	0.56	-				

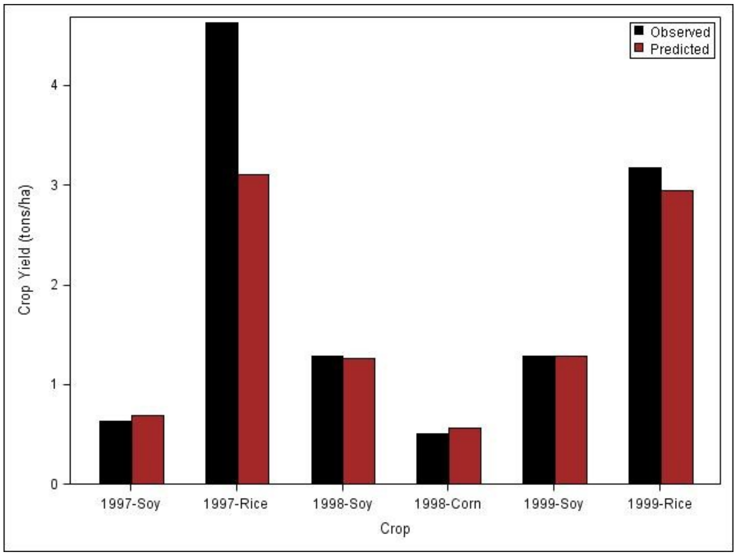

Figure 4.27 Crop Yield Comparison Under Direct Planting

4.5 Summary

The overprediction of runoff under conventional tillage is outside of the acceptable standards for some of the statistics used for evaluation (Ramirez et al., 2012, Moriasi et al., 2007). This could be due to several reasons, including problems in the observed data and limitations of the model structure. Several large precipitation events showed smaller observed runoff than expected. Conventional tillage is expected to produce the largest amount of runoff, which did not occur in this study (Bhatt and Khera, et al., 2006, Busari, et al., 2015). The data used for calibration was the average runoff from three different fields, and some discrepancy was observed between the fields, as discussed above. This variation could contribute to the overestimation of the model, while the large variation of some of the fields under consistent management practices show that problems exist in the data. The small size of the fields can also contribute to the errors in the model (Fu et al., 2011, Ramirez-Avila et al., 2017). With a smaller size, the model is more sensitive to any inaccuracy or variation in the precipitation data. While the other management practices met the statistical recommendations for accurate modeling of runoff, they are also subject to the variability in modeling results due to precipitation. The fields are in the same area and are subject to the same precipitation and the period of El Niño observed during the study (1997 and 1998). El Niño affected the rainfall variability by causing a longer dry period with little rainfall (Grimm, et. al., 2000). This increased variability and the small size of the plots is likely the reason for the smaller correlation of runoff for each of the management practices, especially the over prediction under conventional tillage. As seen in Figure 4.3, the larger over predictions of runoff under conventional tillage occurred in 1997 and 1998, the periods affected by El Niño. Similar trends in the over prediction of runoff are also seen under reduced tillage for the same time period (Figure 4.7).

The predicted monthly sediment yield for every management practice was not satisfactory according to the standards outlined from other sources. While the larger time periods (annual and biannual) show a better agreement, the monthly simulations were not satisfactory and showed underprediction for conventional and reduced tillage and slight overprediction for direct planting. Several studies have cited inaccurate representation of sediment yield in APEX and other models, for a number of reasons (Bhatt and Khera, 2006, Busari, et al., 2015, Ramirez-Avila et al., 2017). Like runoff, the observed sediment data contained some discrepancies. While suspended sediments were measured for each event, the total sediment load was only calculated based on information given for the entire month. This lack of event-based sediment yield in the observed data was likely the reason for the large discrepancies in the model (Bhandari, et. al., 2016). With only monthly values available for calibration, there was a limited amount of data, also contributing to the limited correlation and agreement between modeled and observed sediment yield (Kumar, et. al., 2011). While the overall annual agreement between observed and predicted sediment yield was acceptable, the monthly specific data subject to the event-based or daily sediment yield were not accurately represented by APEX. The study was successful in representing the overall trend of sediment yield under different management scenarios but failed to capture the specific monthly values necessary for further application.

With limited data for sediment, variability in the precipitation, and discrepancies among the fields under the same management, several sources of error were present in the model and helped identify the challenges that occur in the APEX model and the result of errors in data collection and modeling.

4.6 Management Practice Analysis

The runoff, soil loss, and crop yield modeled from reduced tillage and no tillage practices were compared to the results for conventional tillage to better understand the effectiveness of the different management practices. The mean annual values for runoff, sediment yield, and crop yield were used for this comparison. The monthly and daily means for runoff and the monthly means for sediment were also compared to further understand the effects of the different management practices; however, the mean annual reduction is of highest interest for the overall comparison. The observed and predicted annual cumulative values for each management practice for runoff, sediment yield, and crop yield, are represented in Figures 4.28-4.33.

The implemented reduced tillage practices are expected to reduce runoff and sediment yield, while maintaining crop growth (Bhatt and Khera, 2006). Many studies have supported the effectiveness of this practice in runoff reduction; however, the results from the observed and predicted data for runoff showed an increase in the mean annual runoff under reduced tillage (Busari, et al., 2015, Bhatt and Khera, 2006, Lal, 1993). The predicted annual runoff under conventional tillage is 215.33 mm and under reduced tillage is 280.97 mm. The observed data shows a similar increase. This difference is statistically significant, with the p-value 0.0105. This difference in the predicted runoff was represented by a percentage increase of 30.48% for the predicted runoff while the observed difference was 62.84%. The increase in runoff under reduced tillage could be in part because of the variable weather conditions (El Niño) that could affect the runoff simulation. However, the observed data produced an increase in runoff under reduced tillage as well. This field and model showed that tillage is not always effective as a runoff control management practices when implemented alone. Additional control measures could be needed to increase the effectiveness of erosion and runoff control. Sediment yield has a similar increase under reduced tillage. The mean annual sediment yield under conventional tillage was 2.19 Mg/ha and under reduced tillage was 2.51 Mg/ha. This resulted in a 14.61% increase in sediment yield using the model prediction. The measured data shows an 18.35% increase is sediment yield. However, this increase is not significant statistically, with a p-value from the t-test of 0.82, showing that for these field characteristics, reduced tillage does not significantly affect the sediment yield when compared to conventional tillage. Crop yield was slightly affected by the implementation of reduced tillage practices. The soybean yield was reduced by 3%, the corn yield was reduced by 36.9%, and the rice yield was increased by 10.5% under reduced tillage. Although these changes occurred under reduced tillage, they are not significant statistically, with a p-value of 0.8044. Overall, the only significant change under reduced tillage was the increase in runoff. This is not an expected result; however, it is consistent with the observed data. The results were summarized in Tables 4.10-4.15.

As expected, direct planting resulted in a decrease in runoff. The mean annual runoff under direct planting was 151.32 mm, compared to 215.33 mm under conventional tillage. This difference was not statistically significant according to the difference in the means for each year, with a p-value of 0.8929. The change in mean annual runoff results in a 29.73% decrease, proving that direct planting was an effective management practice to reduce runoff for these field characteristics. The change in sediment yield under direct planting practices was not consistent with what was expected. The mean annual sediment yield under direct planting was 2.33 Mg/ha, while under conventional tillage it was 2.19 Mg/ha. This results in a 6.39% increase in sediment load; however, this increase was not significant with a p-value of 0.9117. Crop yield was negatively impacted under direct planting, as expected, with a 16.9% reduction in soybean yield, a 14.4% reduction in rice yield, and a 45.6% reduction in corn yield. This decrease is statistically significant at the 95% confidence interval, with a p-value of 0.0149. This supports the hypothesis that direct planting helps control the amount of runoff but decreases the crop yield significantly. These results are summarized in Tables 4.16-4.21.

Table 4.16 Comparison of Runoff Data for Each Management Practice

		First Half of the Year (Rice/Corn)		Second Half of the Year (Soy)	
		Observed (mm)	Predicted (mm)	Observed (mm)	Predicted (mm)
1996	Conventional	-	-	99.08	102.13
	Reduced	-	-	79.12	188.97
	Direct Planting	-	-	81.27	172.65
1997	Conventional	56.12	47.76	41.08	22.21
	Reduce	148.5	128.49	47.64	36.18
	Direct Planting	47.79	62.8	25.1	27.39
1998	Conventional	62.29	79.16	15.75	45.59
	Reduced	119.43	209.9	15.57	51.71
	Direct Planting	52.79	45.13	9.7	0.97
1999	Conventional	173.26	186.98	63.9	140.32
	Reduced	196.68	206.65	316.29	301.98
	Direct Planting	137.52	144.86	151.15	151.49

Table 4.17 Percent Reduction in Runoff Under Different Management Practices

	Annual		Monthly		Daily	
	Mean (mm)	Percent Reduction (%)	Mean (mm)	Percent Reduction (%)	Mean (mm)	Percent Reduction (%)
Conventional	215.33		39.15		1.74	
Reduced	280.97	-30.48	80.30	-105.11	2.16	-24.14
Direct Planting	151.32	29.73	15.52	60.36	1.22	29.89

Table 4.18 Comparison of Sediment Yield Data for Each Management Practice

		First Half of the Year (Rice/Corn)		Second Half of the Year (Soy)	
		Observed (Mg/ha)	Predicted (Mg/ha)	Observed (Mg/ha)	Predicted (Mg/ha)
1996	Conventional	-	-	1.54	0.432
	Reduced	-	-	4.54	2.36
	Direct Planting	-	-	1.21	1.42
1997	Conventional	5.28	5.13	0.53	0.164
	Reduced	2.45	1.709	0.44	0.537
	Direct Planting	2.27	2.1	0.36	0.26
1998	Conventional	0.44	1.47	0.33	0.62
	Reduced	0.03	0.51	0.49	0.89
	Direct Planting	1.34	2.23	-	-
1999	Conventional	0.96	0.41	1.74	0.36
	Reduced	2.94	3.31	1.77	0.73
	Direct Planting	2.68	2.11	1.84	1.19

Table 4.19 Percent Reduction in Sediment Yield Under Different Management Practices

	Annual		Biannual		Monthly	
	Mean (Mg/ha)	Percent Reduction (%)	Mean (Mg/ha)	Percent Reduction (%)	Mean (Mg/ha)	Percent Reduction (%)
Conventional	2.19		1.25		0.49	
Reduced	2.51	-14.61	1.44	-15.20	0.56	-14.29
Direct Planting	2.33	-6.39	1.55	-24.00	0.49	0.00

Table 4.20 Comparison of Crop Yield Data for Each Management Practice

		First Half of the Year (Rice/Corn)		Second Half of the Year (Soy)	
		Observed (Mg/ha)	Predicted (Mg/ha)	Observed (Mg/ha)	Predicted (Mg/ha)
1997	Conventional	4.23	3.88	0.76	0.77
	Reduced	4.7	3.35	0.85	0.84
	Direct Planting	4.63	3.11	0.63	0.69
1998	Conventional	0.97	1.03	1.48	1.6
	Reduced	1.41	0.92	1.97	2.15
	Direct Planting	0.51	0.56	1.29	1.26
1999	Conventional	3.27	3.2	1.36	1.52
	Reduced	3.27	2.99	1.09	1.2
	Direct Planting	3.18	2.95	1.29	1.29

Table 4.21 Percent Reduction in Crop Yield Under Different Management Practices

		Mean (ton/ha)	Percent Reduction (%)
Conventional	Soy	1.3	
	Rice	3.54	
	Corn	1.03	
Reduced	Soy	1.34	-3.08
	Rice	3.17	10.45
	Corn	1.41	-36.89
Direct Planting	Soy	1.08	16.92
	Rice	3.03	14.41
	Corn	0.56	45.63

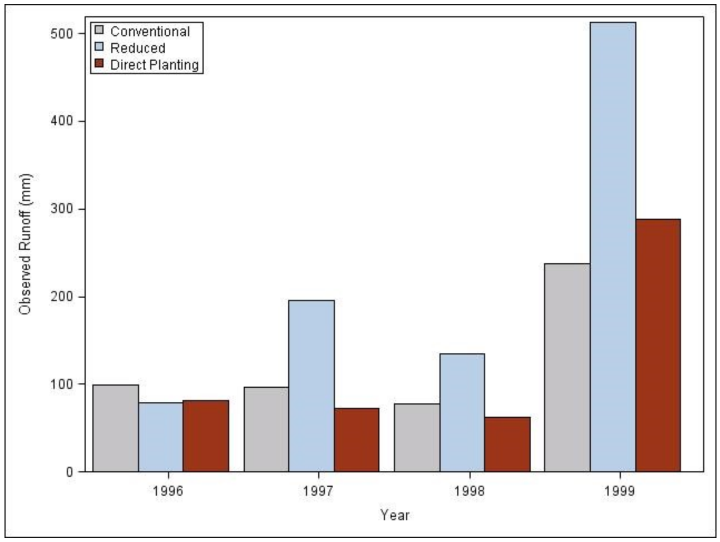

Figure 4.28 Annual Observed Runoff

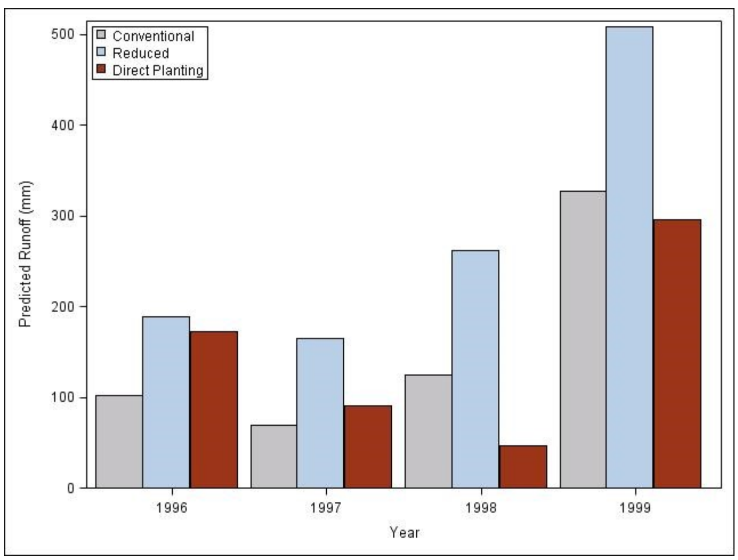

Figure 4.29 Annual Predicted Runoff

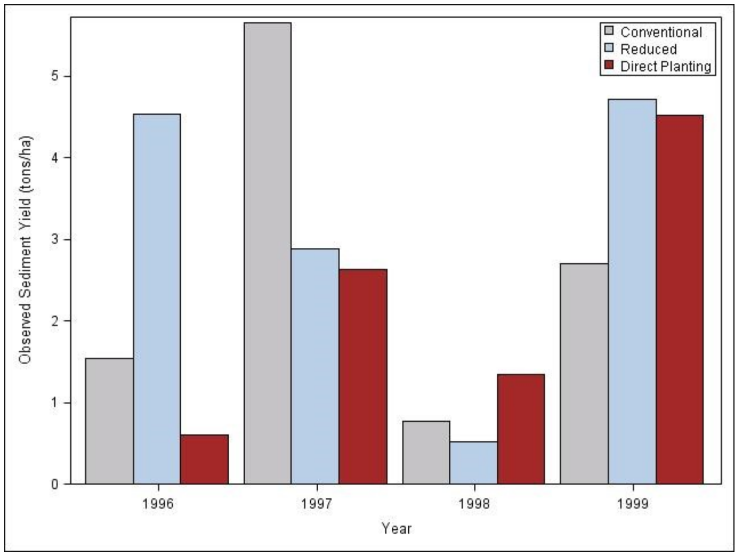

Figure 4.30 Annual Observed Sediment Yield

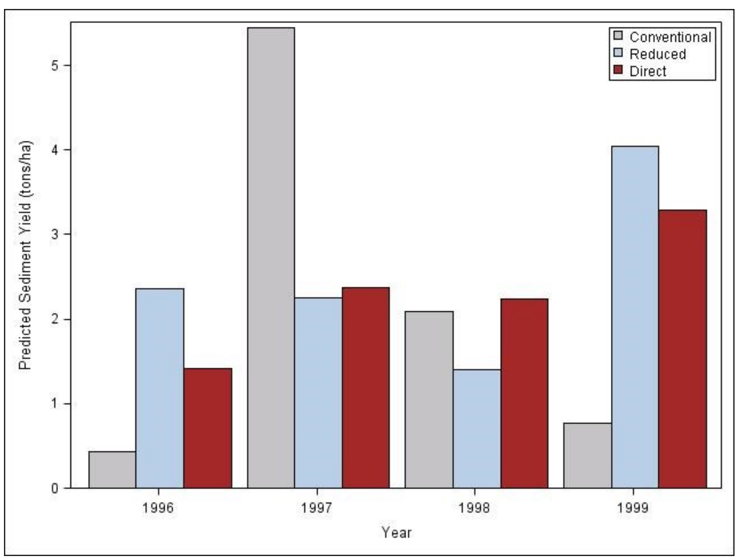

Figure 4.31 Annual Predicted Sediment Yield

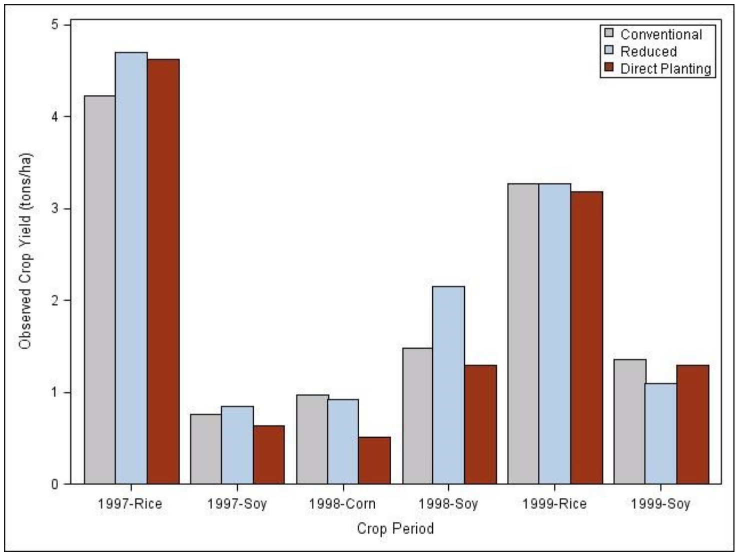

Figure 4.32 Observed Crop Yield

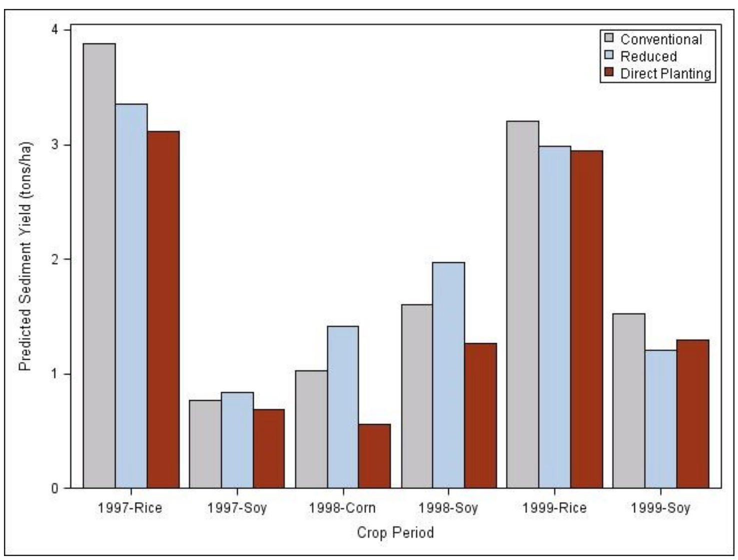

Figure 4.33 Predicted Crop Yield

CHAPTER V

CONCLUSIONS

The performance of APEX to simulate runoff and soil erosion from soils on agricultural production under different tillage practices in the Llanos Orientales region of Colombia was evaluated. APEX was also used to understand how proposed best management practices could help to improve agricultural activities in the region, as far as total gain from the crop yield and the least amount of runoff and soil erosion.

Runoff and crop yield were, in general, successfully predicted by APEX following initial model setup, calibration, and model performance evaluation. Despite the fact that databases included in APEX for soils, weather and crops are mostly functional for the United States, the specific characteristics of these parameters for the Llanos Orientales of Colombia were satisfactorily added and represented by the APEX model.

Predictions for soil loss were not accurate when comparing observed and predicted monthly loads for all evaluated tillage scenarios. Predictions improved, but were not satisfactory, when comparing annual and bi-annual losses. Other studies have also found that predicting soil erosion at the plot scale using APEX, as in this study, makes it more difficult to calibrate and accurately represent soil erosion with the model (Ramirez-Avila et al., 2017, Nelson et al., 2017). The USLE based equations often used for model prediction are designed for annual yield estimations, therefore the lower temporal resolution of this study could have caused inaccuracies when estimating soil loss with the Modified Universal Soil Loss Equation. Inclusion of physically developed models in the estimation of soil loss could improve the modeling performance. Models like WEPP (Water Erosion Prediction Project) have been proven to more accurately represent soil loss (Tiwari, et al., 2000).

Any uncertainty in the runoff estimation and the evident uncertainty in the soil loss estimation can also be attributed to issues in the data collection and uncertainty in the observed data. Crop yield is accurately represented in this model and includes calibration with the biannual or seasonal estimations of the three different crops grown (soybean, corn, and rice). With further review of the data to better understand the data quality, the model could be improved and used to project the scenarios for long term impacts of different tillage practices on the tropical soils. With economic information included, the model can also be used to review the overall impacts- environment, social, and economical- to further determine the best management practices for these fields. This can maintain crop growth while reducing the impacts on the surrounding environment and adding to the profit for the farmer.

A calibrated APEX model could be used to predict runoff and crop yield responses under different management practices in the Llanos Orientales of Colombia but needs improvements for prediction of soil erosion in these tropical soils.

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