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Quantifying Soil Moisture Distribution at a Watershed Scale

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1. Introduction

Soil moisture content is a very vital component of the hydrological cycle. It is a key variable controlling water and energy fluxes in soils (Vereecken et al. 2007). It provides the plant-available transpirable pool of water for vegetative life. In addition, the availability or retention of moisture in the soil controls the rainfall-runoff process. Despite its importance to vital lives and ecosystem, the distribution of soil moisture varies tremendously over the time and space. Spatial patterns of soil moisture are determined by a number of pysiographic factors that affect vertical and lateral redistribution of water in the unsaturated zone. These include topography and landscape position, slope aspect, vegetation, and texture. Temporal patterns depend on meteorological factors and their variation over the time. During the dry period (nonrainly periods), spatial variation in soil moisture is controlled by vegetation (Seyfried and Wilcox 1995). Different vegetation will have different impacts on soil moisture as their uptake will vary widely. Moisture content also exerts a strong control on soil biogeochemistry including microbial activity, nitrogen mineralization, and biogeochemical cycling of nitrogen and carbon (Turcu et al. 2005). Therefore, understanding the spatio-temporal distribution and quantity of available soil moisture that can be used without damaging the natural ecosystem are keys to sustainable development and prevention of ecosystem decline.

Soil moisture has been traditionally measured through point measurements, which is useful to understand field-scale soil water dynamics (Topp and Ferre 2002), and predominantly developed for applications in agriculture. Recent advancements in remote sensing technologies has developed capabilities that contribute to understanding of soil moisture distribution at very large scales such as large basins or continental or global scales; however, these prediction needs to be validated through a large number of ground based point measurements. It would be difficult to provide such information on a larger scale. Several techniques used in the past to represent spatial variation of soil moisture on a large scale using geostatistical anslyses tools such as kringing and semivariogram analysis, but these require a dense sampling character of the soil moisture field. The concept of temporal stability was able to capture spatial variation but limited to smaller scales (Brocca et al. 2010). Robinson et al. (2008) have extensively reviewed and summarized the challenges and opportunities for soil water content measurement in terms of laboratory, equipment, monitoring, remote sensing, and modelling challenges.

Recent advancement in watershed scale hydrology models have increasingly been adopted for soil and water management (Jha et al. 2007, 2010a, 2010b). These models provide a more holistic approach of modelling complex interconnected and nonlinear hydro-geological movement of water across all physical processes. This study used a watershed scale hydrologic model, called Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998), to quantify long-term variation in spatial distribution of soil moisture on a medium-size watershed located in Midwestern USA. SWAT has been shown to perform well on both large river basins and small watersheds in terms of annual water and sediment yield (Arabi et al. 2006, Gitau et al. 2004, Spruill et al. 2000, and Jha et al. 2011, among may other studies). Gassman et al. (2007) has reviewed over a hundred of peer-reviewed SWAT related peer-reviewed publications, which speaks of the magnitude and reliability of model use for hydrology and water quality analyses.

The combination of favourable climate and fertile soil makes the Midwest one of the most productive agricultural areas in the world. However, this brings an enormous application of fertilizers and manures on the cropland, unmanaged and overapplication, which led water quality problems in the local rivers and ultimately to larger ecosystems, e.g. hypoxia problem in the Gulf of Mexico (Rabalais et al. 1996). Many conservation practices have been proposed and implemented over decades. One such practice is the inclusion of winter cover crops in the traditional corn-soybean rotation. Winter cover crops can reduce nitrogen (N) leaching by extending the growing season and the uptake of N beyond that for corn and soybean (Shepherd and Webb 1999). These crops take up residual N, released by mineralization during fall and spring, and N released from fall-applied anhydrous ammonia. The cover crops then release this N as their residue decays the next spring or summer. While this practice was shown to have a tremendous potential for N reduction (Kaspar et al. 2005, Singer et al. 2011), it might have implication in soil moisture dynamics over a long period of time. This study analyzed the impacts of this conservation practice on spatial distribution of soil moisture.

The main objective of this present study is to use SWAT model to quantify soil moisture distribution on a watershed scale and evaluate the impact of applying cover crop conservation practice on soil moisture content.

2. Methods and materials

2.1 Watershed description

The Raccoon River Watershed (RRW) covers nearly 3,630 mi^2 area in portions of 17 Iowa counties in west central Iowa (Figure 1). The North and Middle Raccoon Rivers flow through the recently glaciated (< 12,000 years old) Des Moines Lobe landform region, a region dominated by low relief and poor surface drainage. In contrast, the South Raccoon River drains an older (> 500,000 years old) Southern Iowa Drift Plain landscape region characterized by higher relief, steeply rolling hills, and well-developed drainage. The RRW is dominated by agricultural row crop production, with over 70% of the areas planted primarily in corn and soybeans. Other main land use includes grassland (16.3%), woodland (4.4%), and urban (4.0%). The grasses and trees generally are scattered throughout the South Raccoon basin on terrain difficult to cultivate. Figure 2 show the land use ypes in the watershed. As explained by the landorm region, north Raccoon is mostly tiled due to inadequate soil drainge property. Figure 3 depicts the tile drainage densitiy in the watershed that was very extenstively done in North Raccoon. The RRW stream system has

been impacted by elevated levels of nitrogen, phosphorus, sediment, and bacteria pollutants during recent decades, primarily from nonpoint sources (Hatfield et al., 2009; Jha et al., 2010; Schilling et al., 2008).

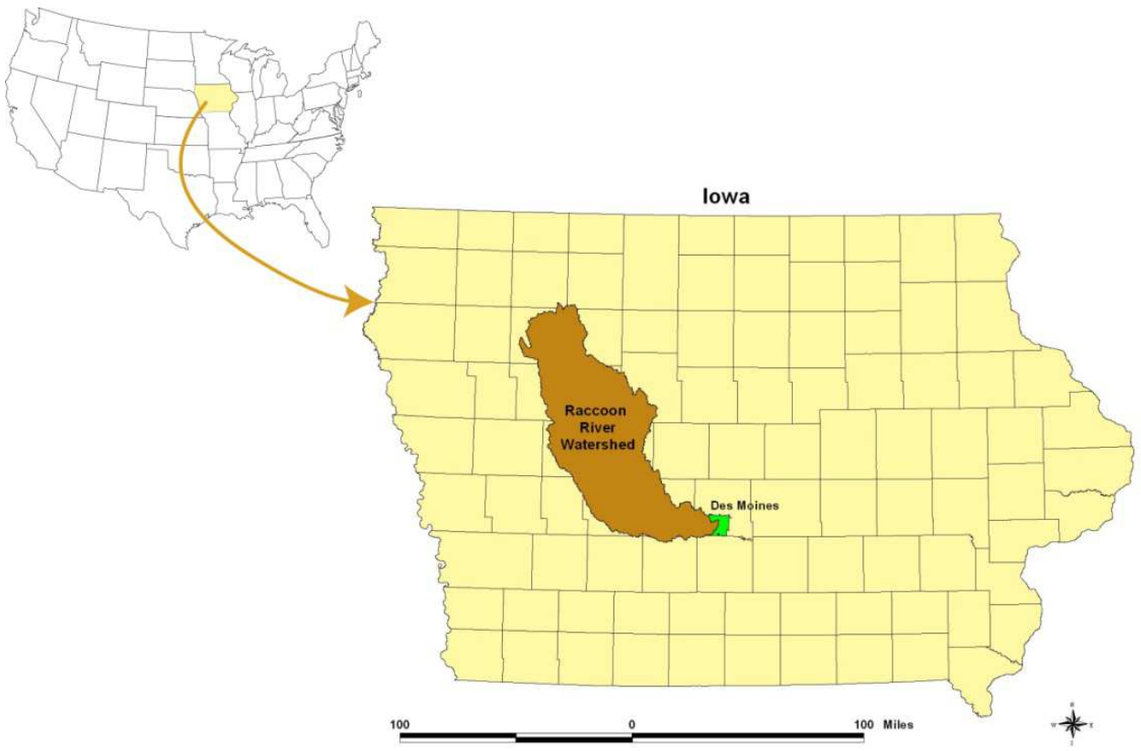

Fig. 1. Location of the study watershed

The modeling framework of the SWAT model for RRW was adapted from Jha et al. 2010. It has used SWAT vesion 2005 and relied on standard 12-digit watersheds (USGS 2009) as a basis for the subwateshed delineation. The process of watershed delineation and HRU creation was performed using the ArcView SWAT interface (AVSWATX). The resulting watershed configuration consisted of 112 subwatersheds. The hydrologica response unites (HRUs) were then created by overlaying Soil Survey Geographic (SSURGO) data (USDA-NRCS, 2008) and 2002 land cover data obtained from IDNR (2008). All together, a total of 3640 HRUs were created for modeling. Daily weather data was obtained from the National Weather Service COOP monitoring sites available through the Iowa Environmental Mesonet (www.mesonet.agron.iastate.edu). AVSWATX assigned the appropriate weather station information to each subwatershed based on the proximity of the station to the centroid of the subwatershed. Ten weather stations were used to provide the temperature and precipitation data for the entire simulation time frame. The SWAT model was run on a daily time step for the 1986 to 2004 period, with the first ten years (1986 to 1995) consisting of a model calibration period and a second nine year period (1996 to 2004) comprising a model validation period. The Penman-Monteith method was selected to estimate potential evapotranspiration and the Muskingum method was selected for channel flow routing simulation. Model calibration required varying model parameters within their ranges for

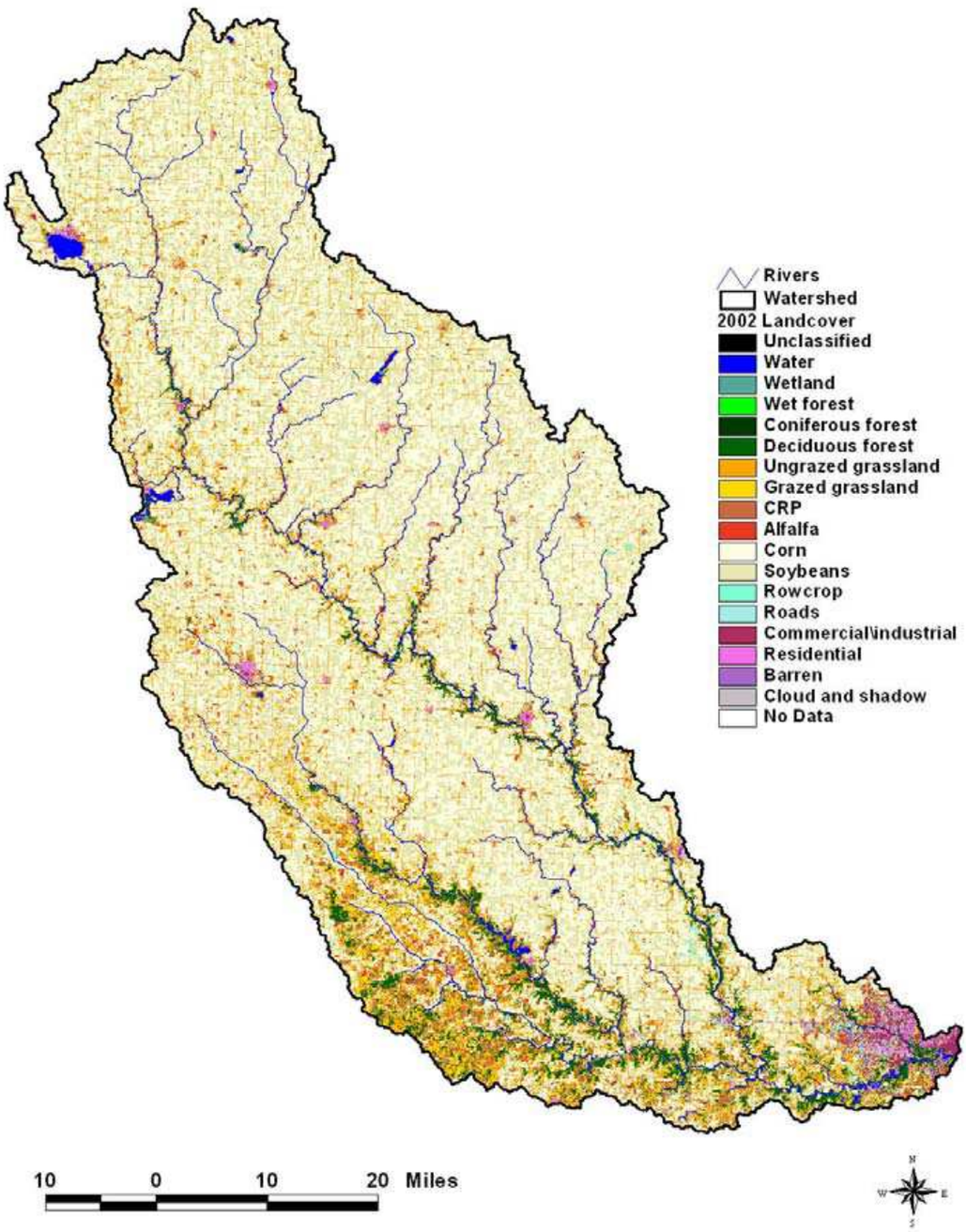

Fig. 2. Land use pattern in the Raccoon River Watershed

match observed variables with the simulated variables. Figure 4 shows the monthly comparison of flow at the watershed outlet for both calibration and validation periods. Details on modeling setup can be found in Jha et al. 2010. Over the entire simulation period, the modeled average annual streamflow at the outlet (220 mm) was very close to the measured value (215 mm). Comparison of monthly values resulted in R^2 and E (Nash-Sutcliffe's coefficient) values of 0.86 and 0.86 for calibraiton and 0.88 and 0.87 for validation.

The modeled average monthly streamflow (18.4 mm) closely matched the measured monthly average (17.9 mm) over the 228 months (19 years) simulation period. These statistical results can be viewed as quite strong for the resutls when viewed in the context of the suggested criteria by Moriasi et al. (2007).

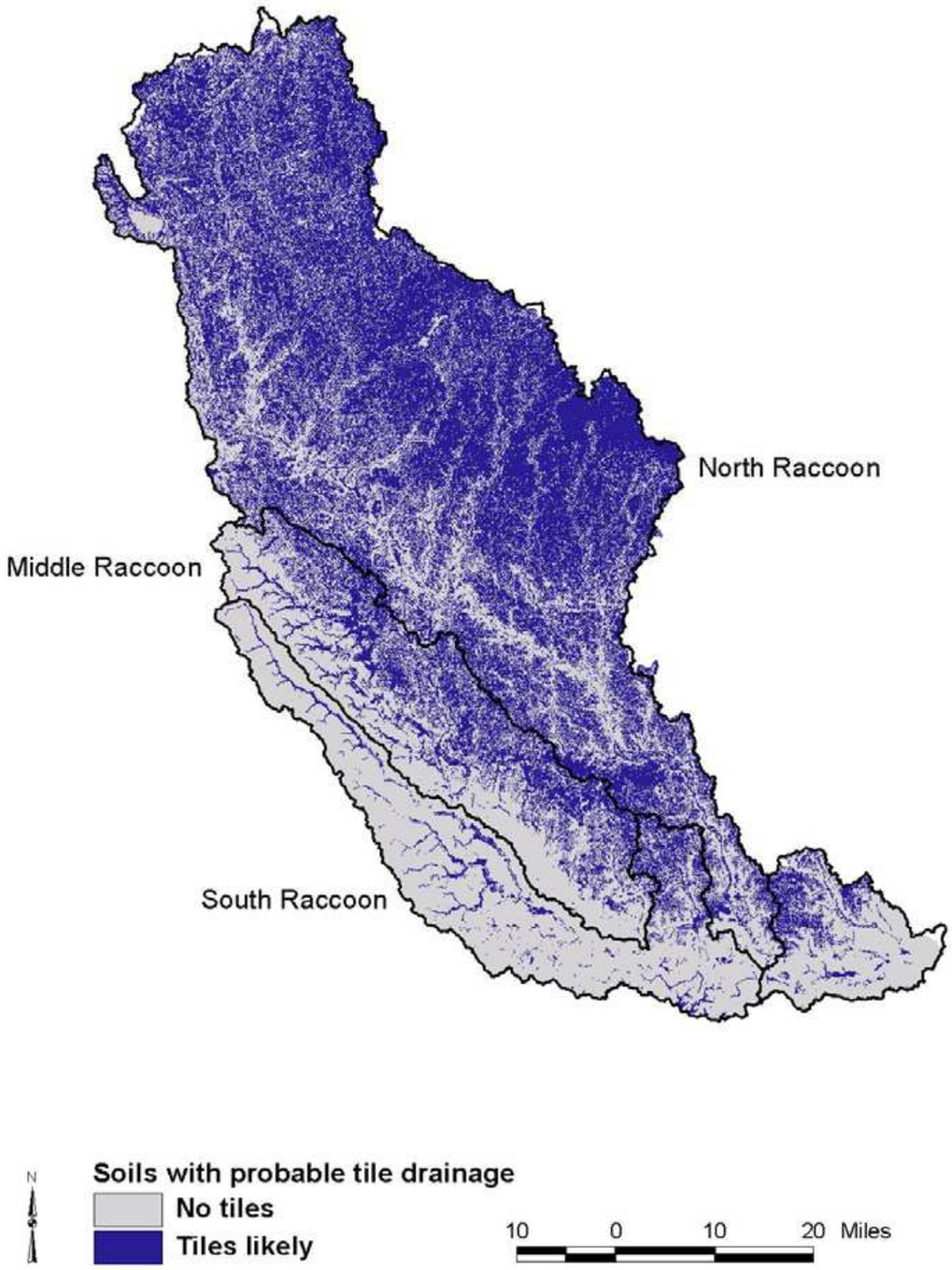

Fig. 3. Soils with probable tile drainage in the watershed (adapted from Schilling et al. 2008)

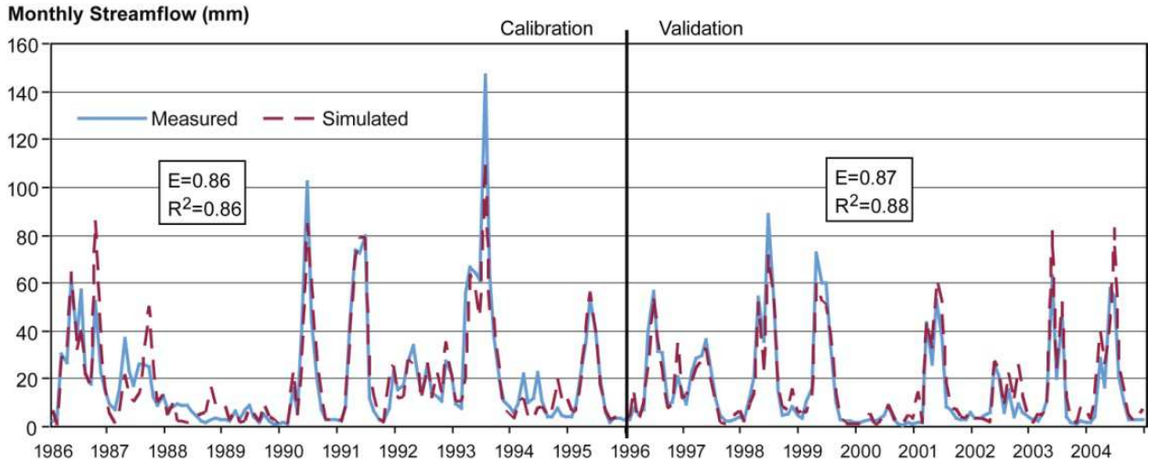

Fig. 4. Long-term average (1986-2004) streamflow comparison at the watershed outlet (adapted from Jha et al. 2010)

2.2 Description of the watershed model, SWAT

The Soil and Water Assessment Tool (SWAT; Arnold et al. 1998) model is a watershed-based hydrologic and water quality model that operates on a daily times step and is capable of modeling the impact of different land use and management practices on hydrology and water quality of the watershed . It was developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) and has experienced continuous evolution since the first releases in the early 1990s. Major model components include hydrology, weather, soil temperature, crop growth, nutrient, bacteria, and land management. In SWAT, watersheds are divided into subwatersheds, which are further delineated by HRUs that consist of homogeneous soil, land use and management characteristics. The HRUs represent percentages of a subwatershed area and thus are not spatially defined in the model. The water balance of each HRU is represented by four storage volumes: snow, soil profile, shallow aquifer, and deep aquifer. Flow generation, sediment yield and pollutant loadings are summed across all HRUs within a subwatershed, and the resulting alues are then routed through channels, ponds, and/or reservoirs to the watershed outlet. The model has several options to estimate potential evapotranspiration including Hargreaves method, Penman-Monteith method, and others. Two options are available to simulate channel routing: variable storage method and Muskingum method. SWAT simulates a complete plant growth process and model nutrient dynamics throughout several interconnected nutrient pools.

Water that enters the soil profile may move along one of several different pathways. The water may be removed from the soil by plant uptake or evaporation. It can percolate past the bottom of the soil profile and ultimately become aquifer recharge. A final option is that water may move laterally in the profile and contribute to streamflow. Of these different pathways, plant uptake of water removes the majority of water that enters the soil profile. Two stages of water content are recognized: field capacity (water held at a tension of 0.033 MPa) and permanent wilting point (water held at a tension of 1.5 MPa). The amount of water held in the soil between field capacity and permanent wilting point is considered to be the water available for plant extraction. SWAT directly simulates saturated flow only. The model records the water contents of the different soil layers but assumes that the water

is uniformly distributed within a given layer. This assumption eliminates the need to model unsaturated flow in the horizontal direction. Unsaturated flow between layers is indirectly modelled with the depth distribution of plant water uptake (Equation 1) and depth distribution of soil water evaporation (Equation 2).
Depth distribution of plant water uptake:

$$w_{\mathrm{up},z} = \frac{E_{\mathrm{t}}}{[1-\exp(-\beta_{\mathrm{w}})]} \cdot [1 - \exp\,(-\beta_{\mathrm{w}} \cdot \frac{z}{z_{\mathrm{root}}})_0] \quad (1)$$

Where $w_{up,z}$ is the potential water uptake from the soil profile to a specified depth, z, on a given day (mm), E_t is the maximum plant transpiration on a given day (m), β_w is the water-use distribution parameter, z is the depth from the soil surface (mm), and z_{root} is the depth of root development in the soil (mm). The potential water uptake from any soil layer can be calculated by solving above equation for the depth at the top and bottom of the soil layer and taking the difference.
Depth distribution of soil water evaporation:

$$E_{soil,ly} = E_{soil,zl} - E_{soil,zu} \quad (2)$$

Where $E_{soil,ly}$ is the evaporative demand for layer *ly* (mm), $E_{soil,zl}$ is the evaporative demand at a lower boundary of the soil layer (mm), and $E_{soil,zl}$ is the evaporative demand at the upper boundary of the soil layer (mm).

2.3 Design experiment for soil moisture analyses

The calibrated SWAT model was examined for predicting the hydrological response at a subwatershed level. The level of spatial detail framed in this study is the size of the subwatershed (total number of which is 112 in the Raccoon River watershed with an average area of about 83.5 km^2). Various hydrological processes including precipitation, water yield, evapotranspiration, and soil water content were looked at from the perspective of spatial distribution across the watershed on a long-term average annual basis. While the spatial distribution of precipitation was derived from historical climatic observation from 10 weather stations located in and around the watershed, other parameters are simulated outcomes from the calibrated SWAT model.
It is hypothesized that the total water yield (surface runoff and baseflow) is very close (if not equal) to the difference between precipitation and evapotranspiration, while soil moisture content remains unaffected over a long-period of time. This hypothesis was tested at a subwatershed level to evaluate the model's ability to predict hydrological processes at smaller spatial scales. There is no set specific criterion to evaluate the hypothesis, but it was assumed that the model performance would be considered acceptable if the bias was found to be less than or equal to 10%. Model prediction of soil moisture was not directly validated by comparing with actual measurement due to the lack of available data on such a large scale (a motivation of this study). However, the reasonable prediction of other hydrological parameters by the model satisfied the validity of the model's ability to replicate hydrological response of the watershed through prediction of hydrological processes.
After the model validation, it was used to evaluate the effect of incorporating winter cover crops into standard corn soybean rotation in the watershed. In this scenario, rye was planted after the corn and soybean harvest. Harvest of the rye crop was not simulated but was simply plowed in prior to corn or soybean planting. This scenario provided an opportunity to assess the impact of adoption of this practice on soil moisture content on a long-term

basis. Winter cover crops provide ground cover on cultivated cropland after the growing season. Rye, oats, and alfalfa have been used as cover crops in cropland areas in the Midwest for number of years, and continuously increasing. It has shown a promise of significant reduction in N losses from agricultural lands (Kaspar et al. 2004) thereby protecting local streams from nonpoint source pollution, and contributing positively to regional ecosystems. Implementation of this practice into vast majority of traditional corn and soybean rotation in the Midwest has potential to reduce N loss significantly, and ultimately reducing the concern of delivering significant nutrient loadings from Iowa and Illinois watersheds into the Mississippi and ultimately to the Gulf of Mexico.

3. Results and discussion

Meteorological input to the modelling system was from 10 weather stations located in and around the watershed. Spatial distribution of the most important hydrological driver precipitation is shown in Figure 5. It can be seen that the distribution does not vary

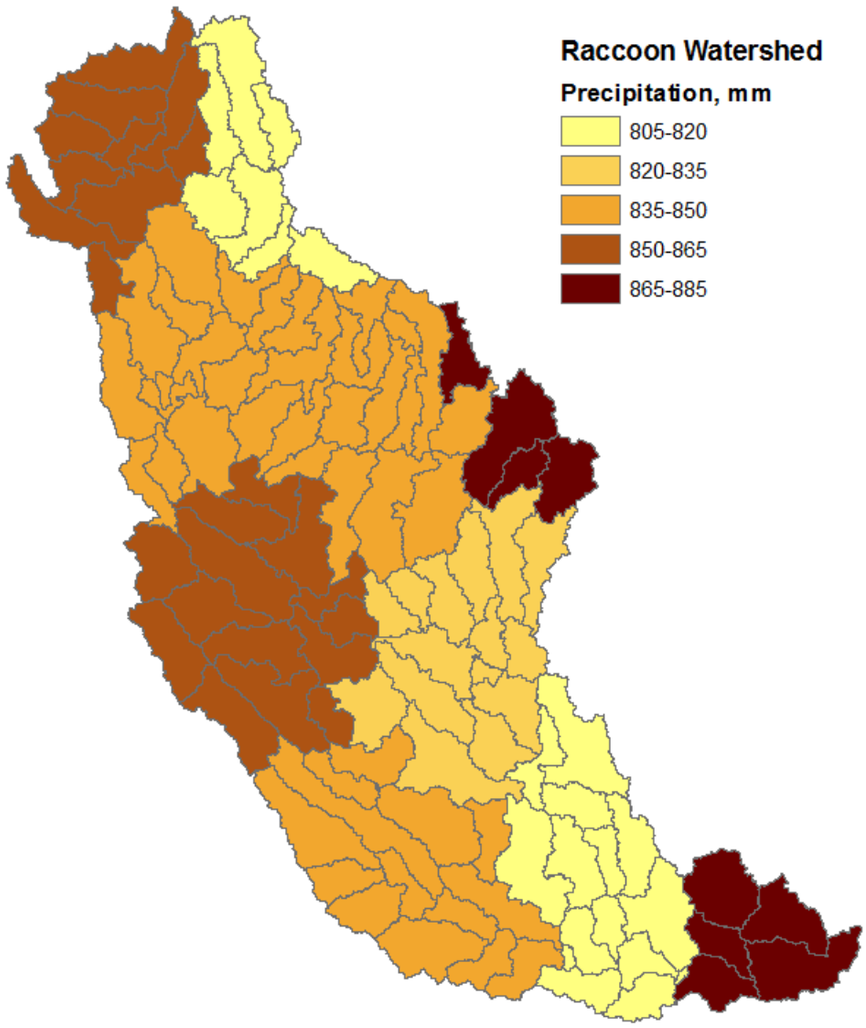

Fig. 5. Spatial representation of precipitation on a long-term annual basis

significantly over the watershed spatially, and values range from 805 to 885 mm on a long-term average annual basis over the period of 19 years (1986-2004). Based on the input on temperature, other meteorological data, and information on land cover, SWAT estimated evapotranspiration (ET) using Penman-Monteith method (Figure 6). Spatial distribution of ET ranged from 470 to 660 mm with higher values in north and central portion of the watershed. Average ET among subwatersheds was found to be 564 mm with standard deviation of 36.

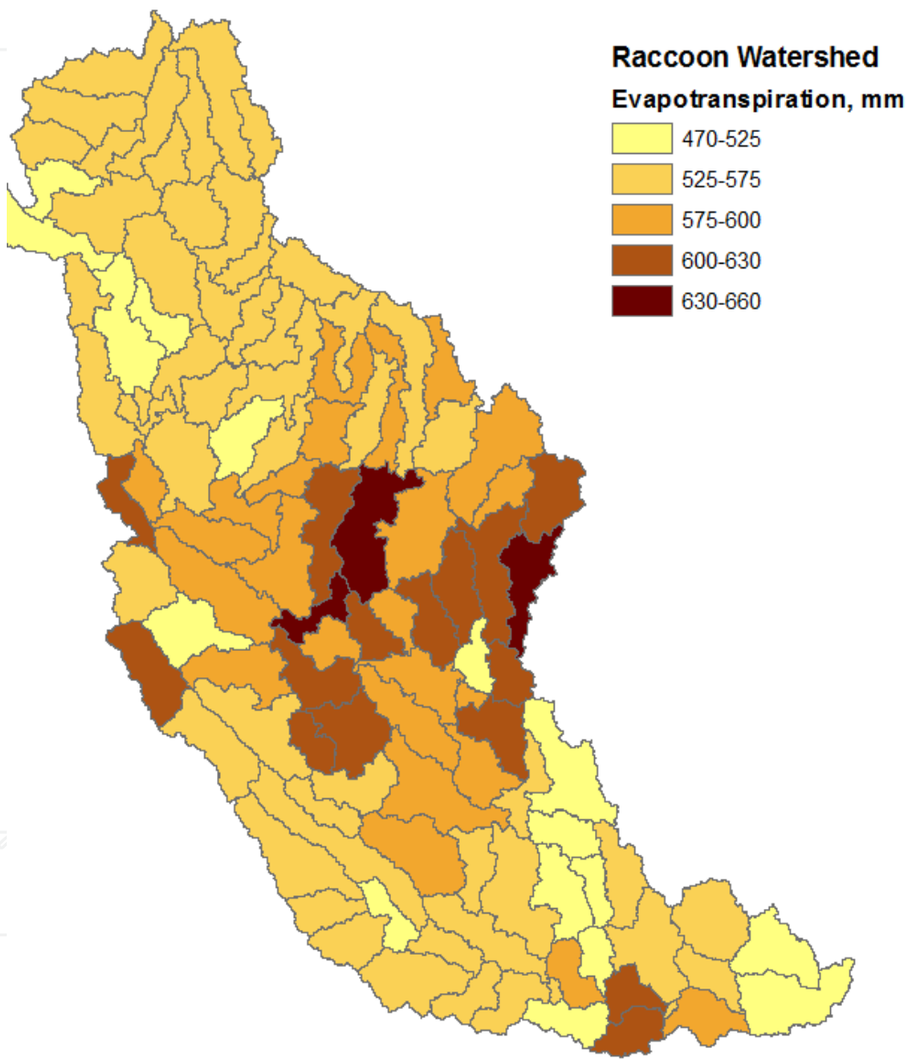

Fig. 6. Estimated evapotranspiration (ET) over a subwatershed scale on a long-term annual basis

Hydrological model performed daily water balance on scale much finer than subwatershed (at HRU or response unit level). The total water yield (sum of surface runoff and baseflow) calculated at each response unit were aggregated at subwatershed level. The distribution of

water yield at the subwatershed level is show in Figure 7. This was achieved after the model was calibrated for overall watershed hydrology and then for time-series data of streamflow at the watershed outlet. Our hypothesis about water yield be equal to precipitation minus evapotranspiration on a long term basis, was tested for each subwatershed individually for the calibrated model. It was found that the absolute deviation of water yield values as compared with the difference in precipitation and evapotranspiration values were very small (mean = 3 mm, standard deviation = 3 mm, and values range from +6 to -10 mm) over the entire watershed. This is the error of less than 1% in predicting water yield on a long-term basis on such a large scale. This validates the accuracy of model prediction on a long-term average annual basis. The resulting soil water content and its spatial distribution are shown in Figure 8. Its value ranges from 164 to 300 mm with an average value of 250 mm and standard deviation of 25mm. Higher moisture content was seem to exist mostly in the eastern portion of the watershed.

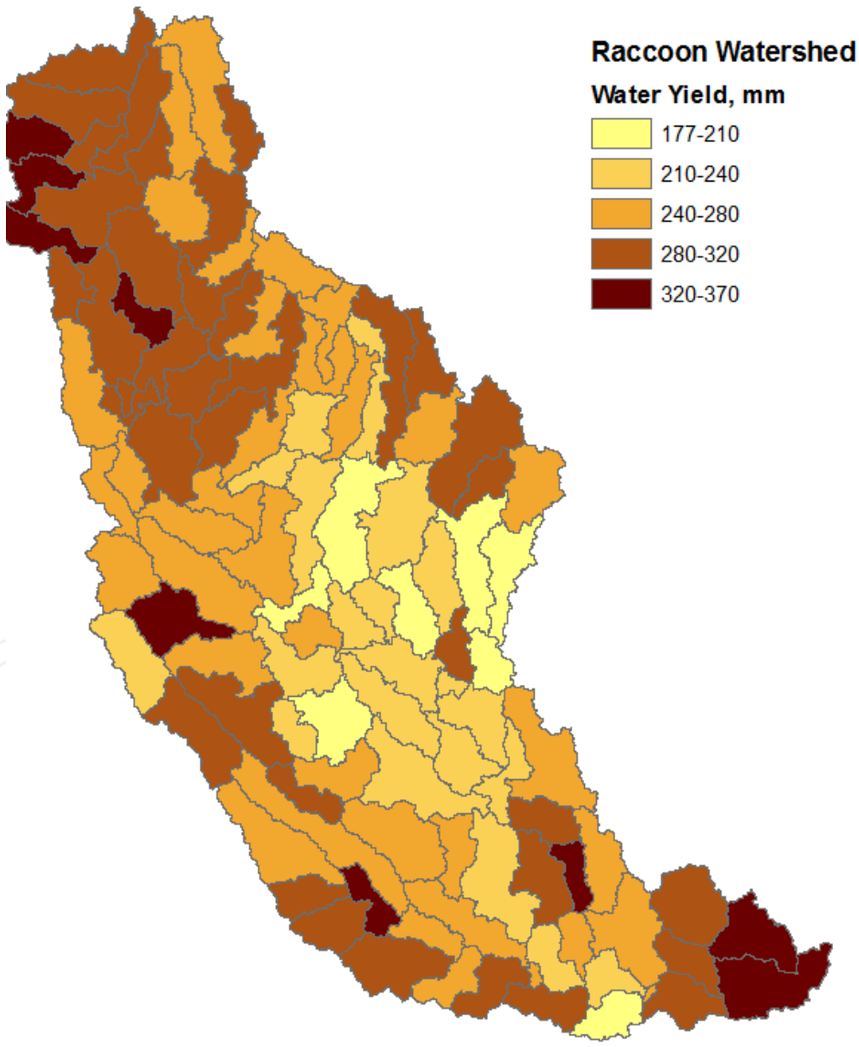

Fig. 7. Total water yield distribution as predicted by SWAT on a long-term basis

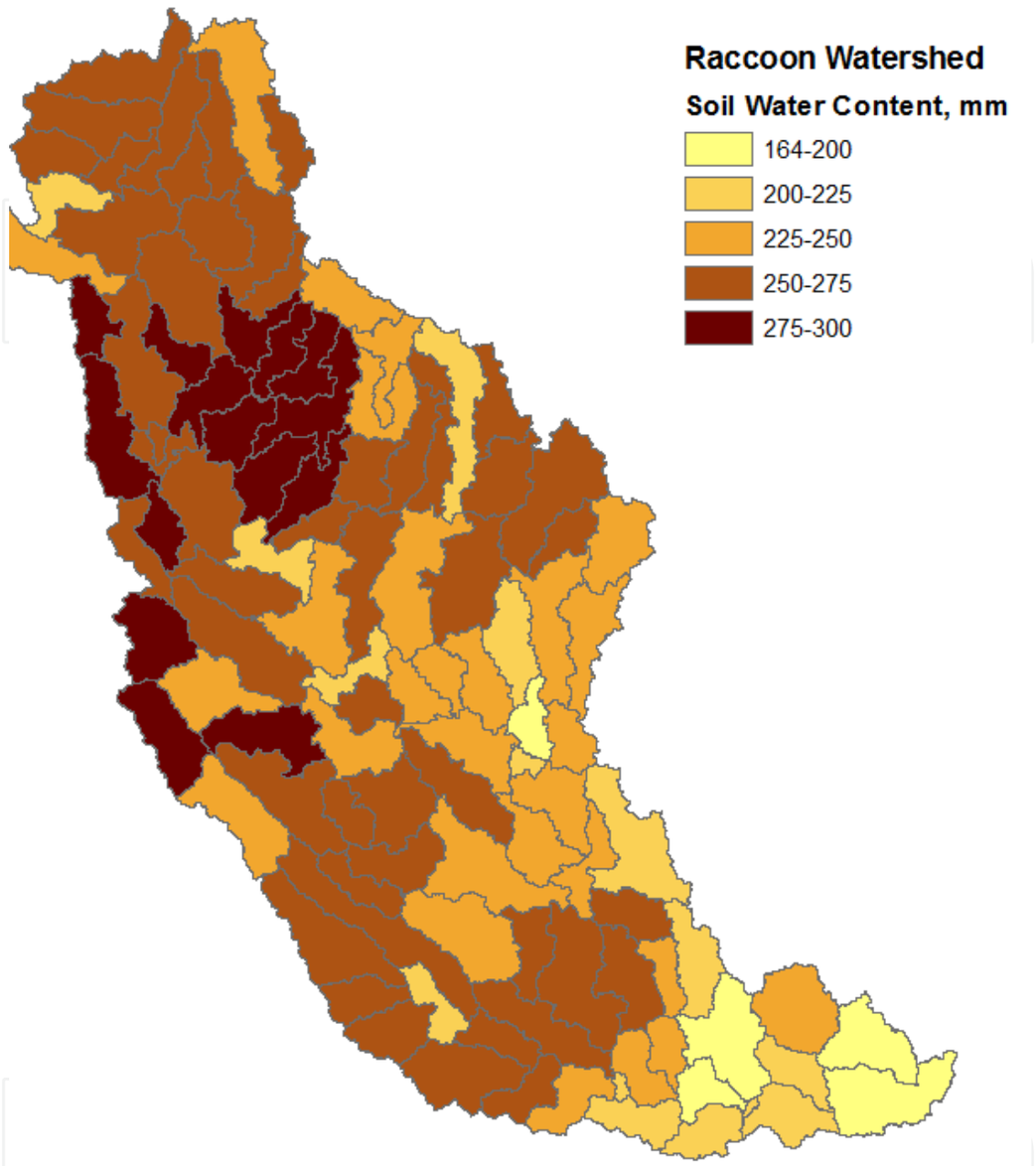

Fig. 8. Soil moisture content predicted by SWAT at subwatershed scale on a long-term basis

Once the model was successfully tested to predict soil moisture content, a scenario was conducted to examine the impact on soil moisture content for a promising land management practice: inclusion of winter cover crops into cropland (corn and soybean in this case). A winter cover crop, rye, was simulated to be planted after corn and soybean harvest each year. While this practice is well known for both soil and water quality and conservation, this study attempts to quantify its impact on soil moisture content. The modelling setup was run with cover crop simulation included into the original baseline condition, and soil moisture content was predicted at each subwatershed. The long-term impact of this management practice on soil moisture content is reflected as shown in Figure 9. Soil moisture content was found to reduce significantly across the watershed with a new mean of 167 mm and

standard deviation of 21. The range of values across subwatershed was found to be 116 to 207 mm, while compared to the baseline condition which was 164 to 300 mm. Spatial distribution of soil moisture was consistent with the original baseline condition where Eastern part of the watershed had higher moisture content. Moreover, the reduction in moisture content was found to be consistent on a spatial scale. The magnitude of reduction was found significant as evident by reduction in mean by 67%. Even though it is an outcome of a simulation model, the signal of impact is very high. Figure 10 show the spatial distribution of reduction in soil water content due to inclusion of winter cover crops in standard corn-soybean rotation on a long-term basis.

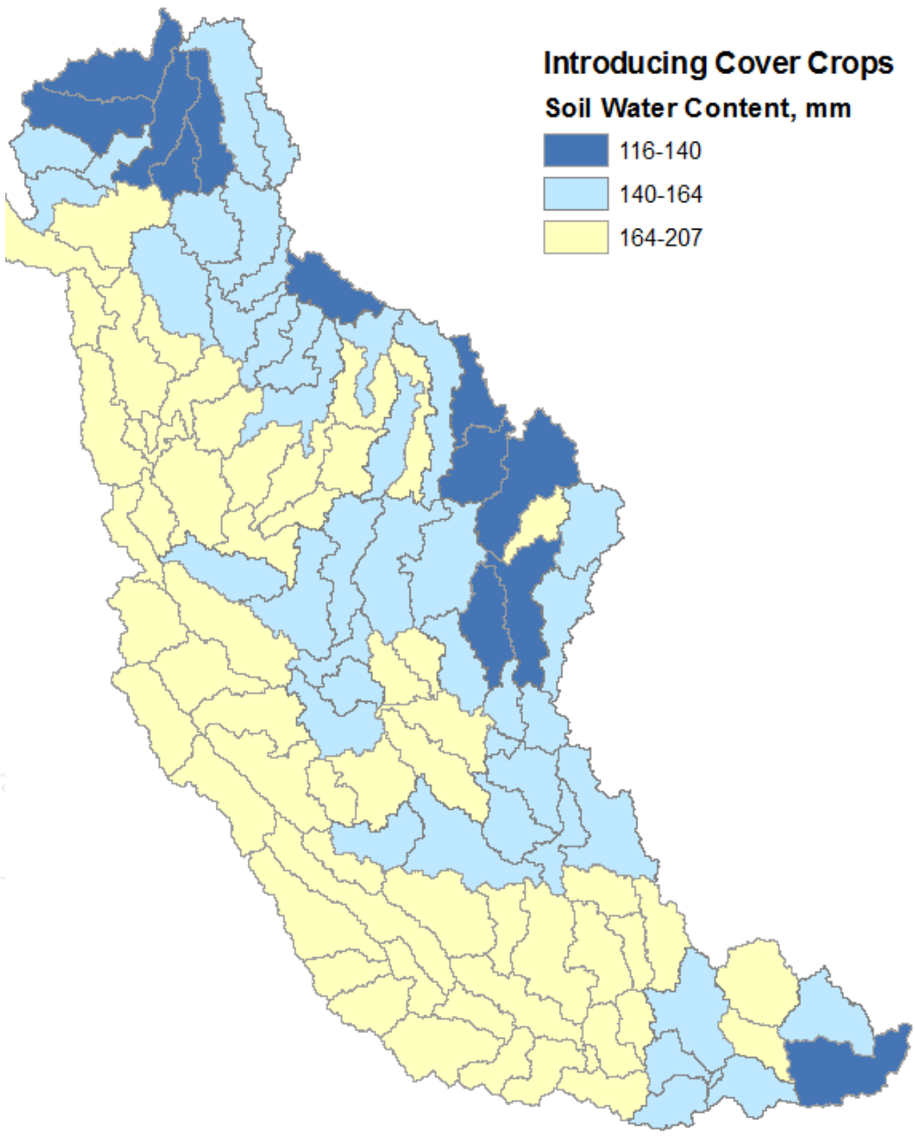

Fig. 9. Soil moisture content (after introducing winter cover crop) as predicted by SWAT at subwatershed scale on a long-term basis

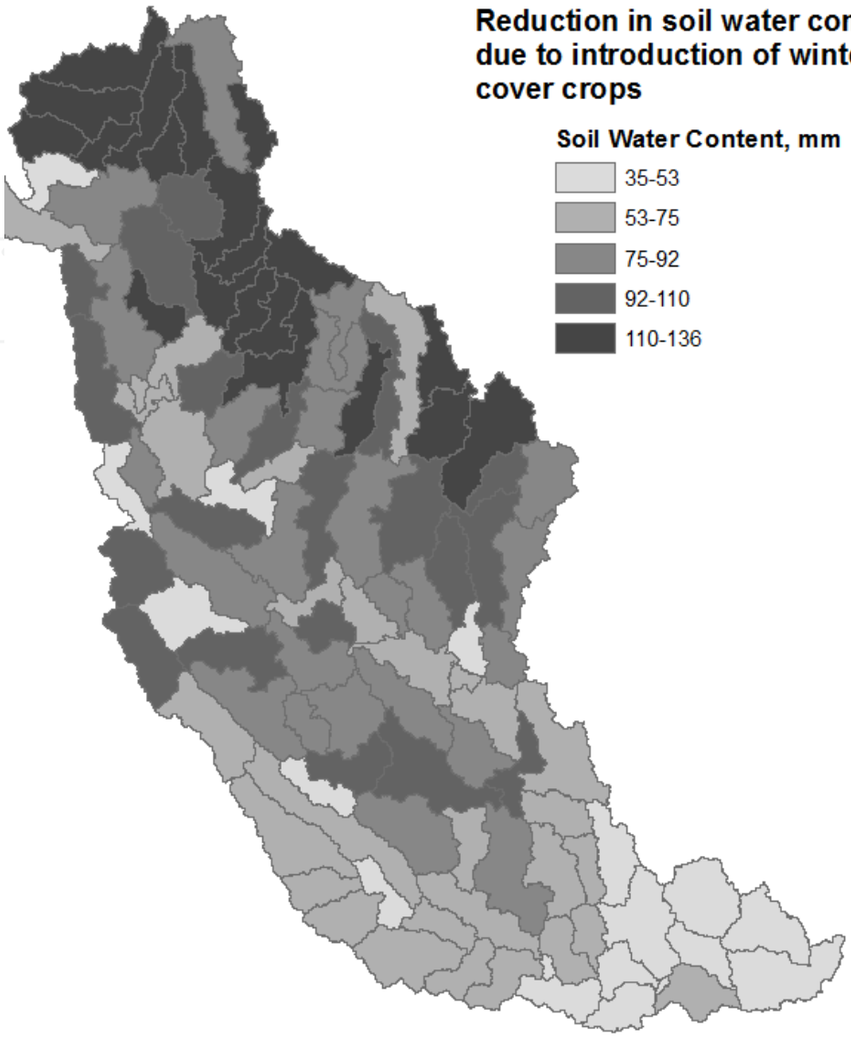

Fig. 10. Reduction in soil moisture content due to inclusion of winter cover crops in standard corn-soybean rotation on a long-term basis

Significant reduction in soil water content raises the sustainability concern of the future crop production and regional ecosystem. As soil water content is very vital for crop growth and other ecosystem variables, it is imperative that it needs to be conserved. Added to that, the uncertainties in climate change with a certain increase of temperature and uncertain changes (may increase or decrease) in the amount of precpitation pose more threat to the sustainable agriculture system. It is warranted that the large scale implementation of winter cover crops should be examined with caution for changes in soil moisture content and its impact on future use of the land for agricultural production.

4. Conclusion

Understanding the spatio-temporal distribution and quantity of available soil moisture that can be used without damaging the natural ecosystem are keys to sustainable development

and prevention of ecosystem decline. This study attempted to quantify the distribution of soil moisture content on a 3,630 mi² Raccoon River Watershed located in the Midwest United States through the use of a watershed scale hydrologic model SWAT. After a successful test of SWAT's ability to predict soil moisture content, it was used to quantify the impact of introducing winter cover crops in standard corn-soybean rotation in the Midwest. The unit of analyses was at a subwatershed scale; a finer unit with total number of 112 comprise the entire watershed. Successful calibration of the SWAT modelling setup for the watershed input parameters and databases was found to produce total water yield very accurately (less than 1% error) which lead to the accurate estimation of soil moisture content at a subwatershed scale. While introducing winter cover crops has shown to be effective positively for both soil quality as well as water quality, this modelling study on the impact of this change in soil moisture found to have an adverse impact on a long-term basis. Soil moisture content was found to reduce significantly across the watershed with a mean of 167 mm and standard deviation of 21. The range of values across subwatershed was found to be 116 to 207 mm, while compared to the baseline condition which was 164 to 300 mm. The magnitude of reduction was found significant as evident by reduction in mean by 67%. Even though it is predicted by simulating a well calibrated model, signal of the impact is very high. It is warranted that the large scale implementation of winter cover crops should be examined with caution for changes in soil moisture content and its impact on future use of the land for agricultural production.

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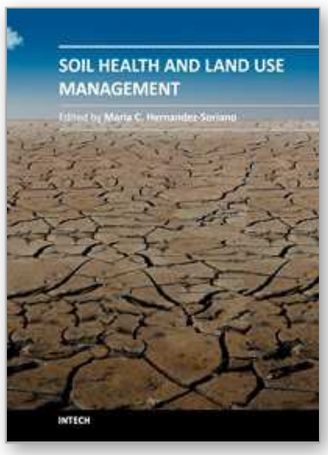

Soil Health and Land Use Management

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Soils play multiple roles in the quality of life throughout the world, not only as the resource for food production, but also as the support for our structures, the environment, the medium for waste disposal, water, and the storage of nutrients. A healthy soil can sustain biological productivity, maintain environmental quality, and promote plant and animal health. Understanding the impact of land management practices on soil properties and processes can provide useful indicators of economic and environmental sustainability. The sixteen chapters of this book orchestrate a multidisciplinary composition of current trends in soil health. Soil Health and Land Use Management provides a broad vision of the fundamental importance of soil health. In addition, the development of feasible management and remediation strategies to preserve and ameliorate the fitness of soils are discussed in this book. Strategies to improve land management and relevant case studies are covered, as well as the importance of characterizing soil properties to develop management and remediation strategies. Moreover, the current management of several environmental scenarios of high concern is presented, while the final chapters propose new methodologies for soil pollution assessment.

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