Asian Journal of Geographical Research

2(2): 1-9, 2019; Article no.AJGR.49417

Effect of Climate Change in the Stream Flow, Crop Yields and NP Levels at White Oak Bayou Watershed Using SWAT simulation: A Case Study

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJGR/2019/v2i230083
Editor(s):
(1) Dr. Hani Rezgallah Al-Hamed Al-Amoush, Associate Professor, Department of Earth and Environmental, Institute of Earth and Environmental, Al al-Bayt University, Jordan.
Reviewers:
(1) P. R. Reddy, India.
(2) Charles Nyambane Onyari, University of Embu, Kenya.
Complete Peer review History: http://www.sdiarticle3.com/review-history/49417

Received 13 March 2019
Accepted 29 May 2019
Published 04 June 2019

Case Study

ABSTRACT

Projected changes in temperature due to global climate change may have serious impacts on hydrologic processes, water resources availability, irrigation water demand, and thereby affecting the agricultural production and productivity. Therefore, understanding the impacts of climate change on crop production and water resources is of utmost importance for developing possible adaptation strategies. The White Oak Bayou, one of the several waterways that give Houston, Texas, United States its popular nickname "The Bayou City" was selected in this case study.

SWAT model is process based and can simulate the hydrological cycle, crop yield, soil erosion and nutrient transport. It is operated with an interface in ArcView GIS using raster or vector datasets including the digital elevation model (DEM), soil properties, vegetation, LULC, and meteorological observations observed which were derived from the Consortium for Geospatial Information, National Cooperative Soil Survey, National Land Cover Database 2006, NCEP Climate Forecast System Reanalysis and USGS website in 2005-2008. The climate change scenario was based on the projected increase in temperature by the IPCC by 2100.

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This case study showed a decrease in streamflow from observed actual scenario (2005-2008) to projected increase of 4°C temperature in future climate change scenario by 2100. The evapotranspiration increased but there was a decrease in surface runoff and percolation.

Moreover, there were greater average plant biomass and more average plant yields. Hence, the nitrogen and phosphorus uptake and removed in yield increased. Thus, the total nitrogen decreased while the total phosphorus is zero indicating loss of the Phosphorus content in the soil. Yet, this case study needs to be validated and calibrated with actual data to support the projected outcome.

Keywords: SWAT; climate change; watershed; crop yield; nitrogen; phosphorus; streamflow.

1. INTRODUCTION

Increases in average global temperatures are expected to be as much as 4°C by 2100, with a likely increase for all scenarios except the one representing the most aggressive mitigation of greenhouse gas emissions. Global average temperature is expected to warm at least twice as much in the next 100 years as it has during the last 100 years [1].

Projected changes in temperature due to global climate change may have serious impacts on hydrologic processes, water resources availability, irrigation water demand, and thereby affecting the agricultural production and productivity. Meanwhile, climate variability is one of the most significant factors influencing year to year crop production, even in high yielding and high-technology agricultural areas [2].

Agricultural productivity is sensitive to climate change due to direct effects of changes in temperature, precipitation and carbon dioxide concentrations, and also due to indirect effects through changes in soil moisture and the distribution and frequency of infestation by pests and diseases [3].

The increase in temperature under climate change scenarios is expected to increase the evapotranspiration (ET) demand. Various studies conducted to study the effects of climate change on the crop production showed that the effect of climate change on crop production varied with the climate change scenario used, current climate, cropping systems, management practices and also from region to region [4,5,6,7,8]. Therefore, understanding the impacts of climate change on crop production and water resources is of utmost importance for developing possible adaptation strategies.

SWAT (Soil and Water Assessment Tool) [9] has been developed to support soil erosion assessment, water resource analysis, and water quality management in agricultural watersheds [10]. SWAT, as a physically-based, spatially distributed hydrological model, has been widely used to simulate the ecological, hydrological, and environmental processes under a range of climate and management conditions since 1993. It is a product of over 30 years of model development by the US Department of Agricultural Research Service, which has been extensively used worldwide.

SWAT model is process based and can simulate the hydrological cycle, crop yield, soil erosion and nutrient transport. While the different versions of SWAT have been widely used throughout the world for agricultural and water resources applications, little has been done to test the performance, variability, and transferability of the parameters in the crop yield along with nutrient level modules in an integrated way. Despite the influence of crop growth on both hydrology and nutrient cycling, calibration of the crop growth component has rarely been reported [11].

The White Oak Bayou, one of the several waterways that give Houston, Texas, United States its popular nickname "The Bayou City" was selected in this case study. Wildlife habitat exists on much of the undeveloped tracts scattered throughout the watershed and has been preserved and/or created in several of the large regional storm water detention basins constructed by the Harris County Flood Control District. 1,494 trees have been planted in area Tribute Groves by Trees for Houston.

Crop growth models are important tools in evaluating the potential growth and yields of crops in different climatic and environmental conditions, including nutrient levels in agriculture watersheds. Hence, hydrology, crop growth and nutrient levels in the basin will be analyzed based on various scenarios specifically the actual condition of the chosen watershed and the projected temperature increase brought by climate change.

2. MATERIALS AND METHODS

2.1 Study Area

The study area was the White Oak Bayou. The Bayou originates northwest, near Highway 6 and U.S. Highway 290/Northwest Freeway, and meanders generally toward the southeast until it joins Buffalo Bayou in downtown Houston (Fig. 1).

The watershed is the 223-km^2 drainage area of the U.S. Geological Survey (USGS) flow gauging station 08074500. According to the area’s digital elevation model [12,13], the average slope of the watershed is 1.2 m/km; and, based on the rainfall data available for the area [14], its average annual precipitation depth is 1420 mm. The soils in the area are loams characterized by high clay content, moderate to very slow drainage and shallow water tables, and are classified under hydrologic soil group D [15].

Wildlife habitat exists on much of the undeveloped tracts scattered throughout the watershed and has been preserved and/or created in several of the large regional storm water detention basins constructed by the Harris County Flood Control District. However, only a little undisturbed wildlife habitat exists along the urban channels of White Oak Bayou and its tributaries [16]. Also along the bayou, between 18th and 11th Streets, is a grove of trees that have been planted by Trees For Houston. The "Tribute Grove" offer individuals the opportunity to commemorate special people or events by planting a tree on White Oak's banks. Since 1997, 1,494 trees have been planted in area Tribute Groves by Trees for Houston [17].

2.2 SWAT Model and Data Collection

The Soil and Water Assessment Tool (SWAT), a semi-distributed hydrological model, was developed to assess the impact of land management and climate on water, nutrient and pesticide transport at the basin scale [9,18]. SWAT simulates hydrological processes such as surface runoff at a daily time scale on the basis of information that includes weather, topography, soil properties, vegetation, and land management practices. In SWAT, the study basin is divided into sub-basins, and each sub-basin is further subdivided into hydrologic response units (HRUs) with homogeneous characteristics (e.g., topography, soil, and land use). Hydrological components are then calculated for the HRUs.

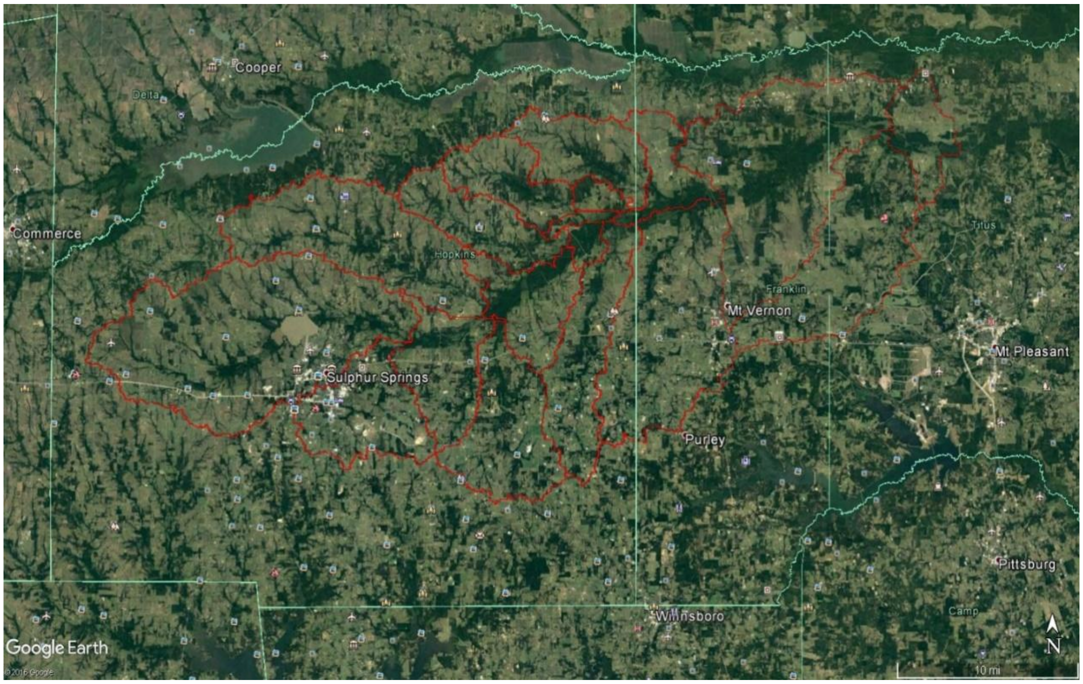


Fig. 1. Location map of the White Oak Bayou watershed, Houston, Texas, United States (SWAT, 2017)

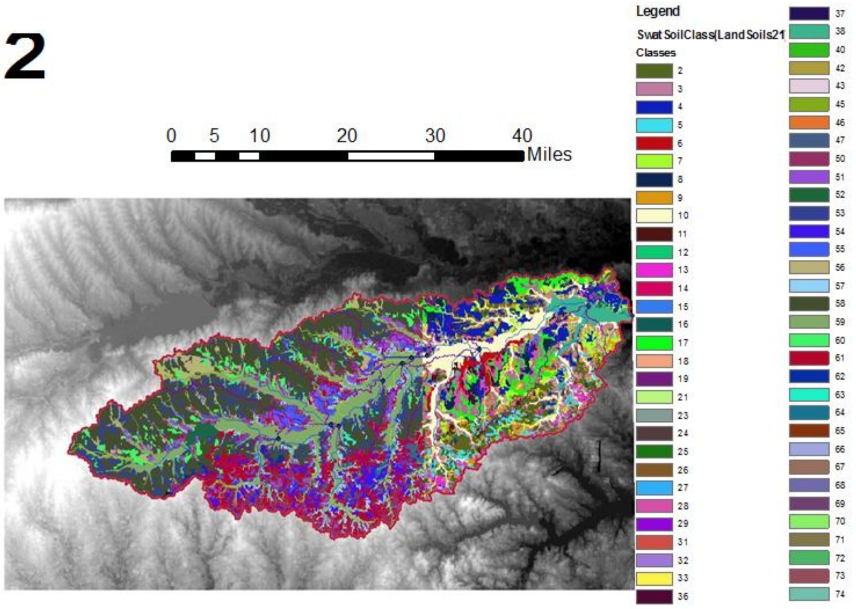


Fig. 2. The soil classes of the White Oak Bayou watershed at Houston, Texas, United States (SWAT, 2017)

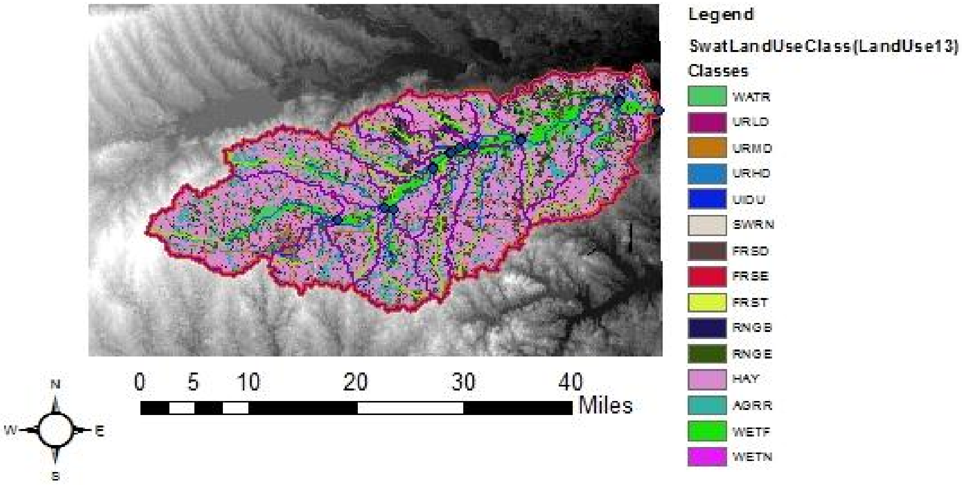


Fig. 3. The land use classification of the White Oak Bayou watershed at Houston, Texas, United States (SWAT, 2017)

In this study, SWAT is operated with an interface in ArcView GIS [19]. Therefore, the required data are either raster or vector datasets including the digital elevation model (DEM), soil properties, vegetation, LULC, and meteorological observations observed which were derived from the Consortium for Geospatial Information, National Cooperative Soil Survey, National Land Cover Database 2006, NCEP Climate Forecast System Reanalysis and USGS website from 2005-2008 (Figs. 2-3).

The climate change scenario was based on the projected increase in temperature by the IPCC [1]. Increases in average global temperatures are expected to be as much as 4°C by 2100, with a likely increase for all scenarios except the one representing the most aggressive mitigation of greenhouse gas emissions. Global average temperature is expected to warm at least twice as much in the next 100 years as it has during the last 100 years (Fig. 4).

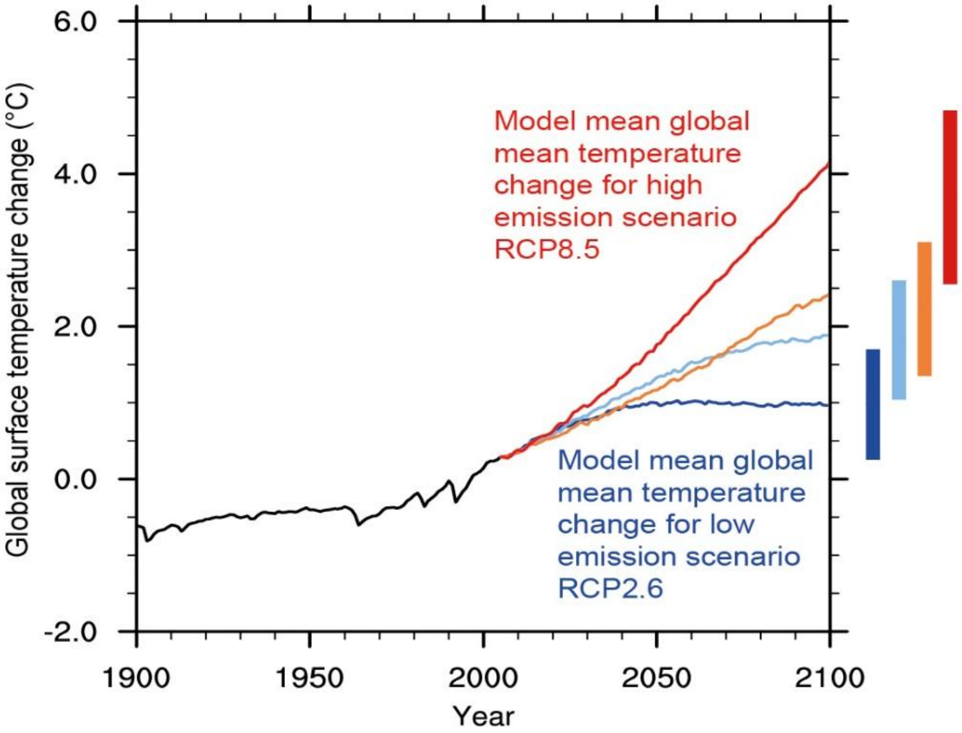
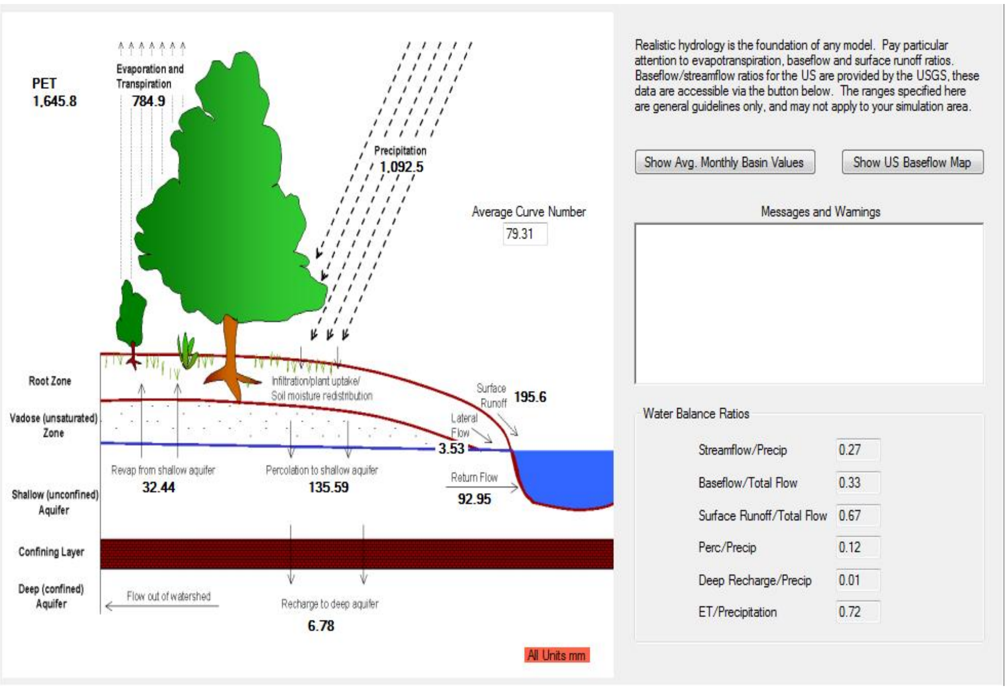


Fig. 4. Observed and projected changes in global average temperature under four emissions pathways. The vertical bars at right show likely ranges in temperature by the end of the century, while the lines show projections averaged across a range of climate models. Changes are relative to the 1986-2005 average (IPCC, 2013)



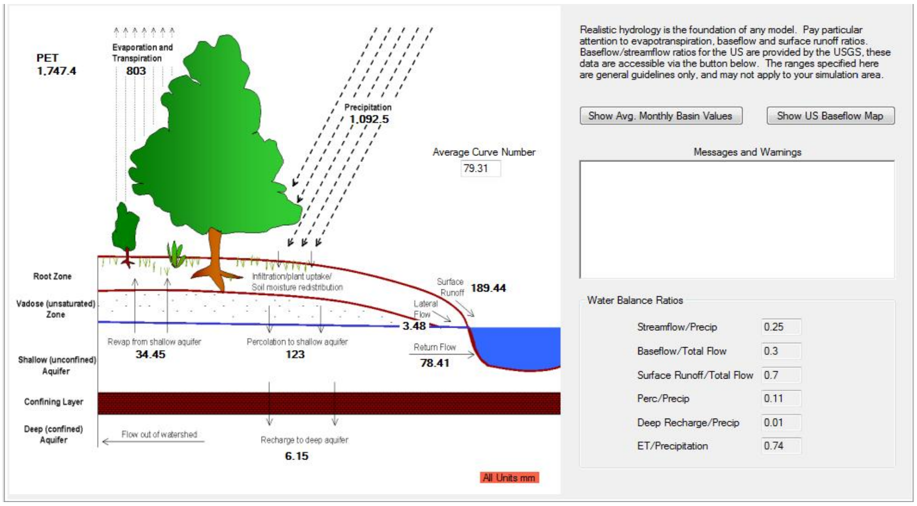
Average Curve Number 79.31

Realistic hydrology is the foundation of any model. Pay particular attention to evapotranspiration, baseflow and surface runoff ratios. Baseflow/streamflow ratios for the US are provided by the USGS, these data are accessible via the button below. The ranges specified here are general guidelines only, and may not apply to your simulation area.

Water Balance Ratios

Streamflow/Precip	0.27
Baseflow/Total Flow	0.33
Surface Runoff/Total Flow	0.67
Perc/Precip	0.12
Deep Recharge/Precip	0.01
ET/Precipitation	0.72

Fig. 5. Hydrological effects under the actual observed scenario from 2005-2008 (SWAT, 2017)



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Average Curve Number: 79.31

Water Balance Ratios

Streamflow/Precip	0.25
Baseflow/Total Flow	0.3
Surface Runoff/Total Flow	0.7
Perc/Precip	0.11
Deep Recharge/Precip	0.01
ET/Precipitation	0.74

Fig. 6. Hydrological effects under future climate change scenario by 2100 (SWAT, 2017)

3. RESULTS AND DISCUSSION

3.1 Hydrological Effects

The hydrological effects between the two compared scenarios, the observed (2005-2008) and the future climate change scenario by 2100 are presented in Figs. 5-6. As observed, the streamflow decreased from 3.53 to 3.48 mm while the evapotranspiration increased from 784.9 to 803 mm in 2100 projected 4°C increase of temperature. There were no observed changes in precipitation but there was a decrease in surface runoff from 195.6 to 189.44 mm. Further decrease in percolation may likely occur from 135.59 to 123.0 mm by 2100.

The same conditions were also reported in the Jinghe River Basin [20], a typical large 20 catchment (> 45000 km^2) located in a semi-humid and arid transition zone on the central Loess Plateau, Northwest China. The simulated results indicated that although runoff increased very little between the 1970s and the 2000s due to the combined effects of LULC and climate changes, LULC and climate changes affected surface runoff differently in each decade, i.e., runoff increased with elevated precipitation between the 1970s and the 1980s (precipitation contributed 88% to the increased runoff). Thereafter, runoff decreased and became increasingly influenced by LULC change, with a 44% contribution between the 1980s and the 1990s and a 71% contribution between the 1990s and the 2000s.

Also, evapotranspiration for both wheat and rice is projected to increase in the range of 3–9.6 and 7.8–16.3%, respectively based on potential future impacts of climate change on irrigated rice and wheat production and their evapotranspiration and irrigation requirements in the Gomti River basin, China [4].

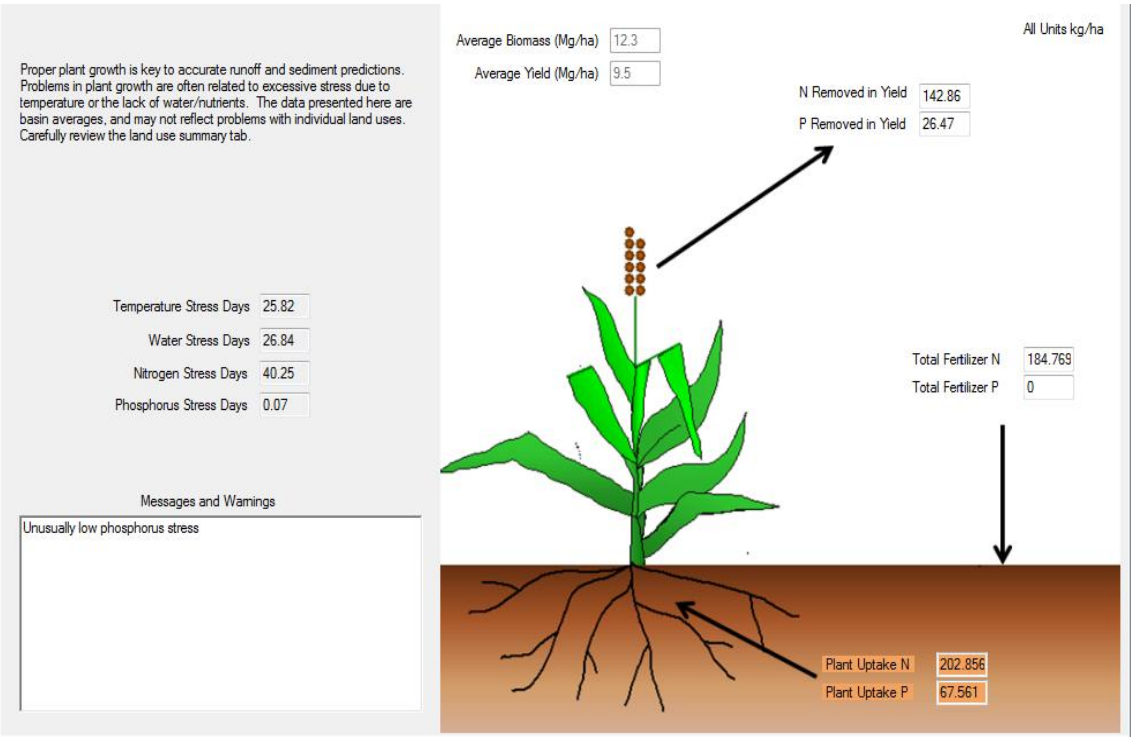
3.2 Plant Growth and NP Levels

The projected plant growth and nitrogen, phosphorus (NP) levels in 2005-2008 compared to the climate change scenario by 2100 is illustrated in Figs. 7-8.

It is noted that with the projected increase of temperature by 4 °C brought by future climate change scenario, there would be greater average plant biomass from 12.3 to 13.6 kg/ha. Hence, more average plant yields from 9.5 to 10.8 kg/ha.

Similarly, simulation results on potential future impacts of climate change on irrigated rice and wheat production in the Gomti River basin, China showed an increase in mean annual rice yield in the range of 5.5–6.7, 16.6–20.2 and 26–33.4 % during 2020s, 2050s and 2080s, respectively. Similarly, mean annual wheat yield is also likely to increase by 13.9–15.4, 23.6–25.6 and 25.2–27.9 % for the same future time periods [4].

With these, the nitrogen and phosphorus uptake and removal would lead to an increase in yield. Thus, the total nitrogen decreased from 184.7 to 158.3 kg/ha while the total phosphorus is zero indicating loss of the Phosphorus content in the soil.



Proper plant growth is key to accurate runoff and sediment predictions. Problems in plant growth are often related to excessive stress due to temperature or the lack of water/nutrients. The data presented here are basin averages, and may not reflect problems with individual land uses. Carefully review the land use summary tab.

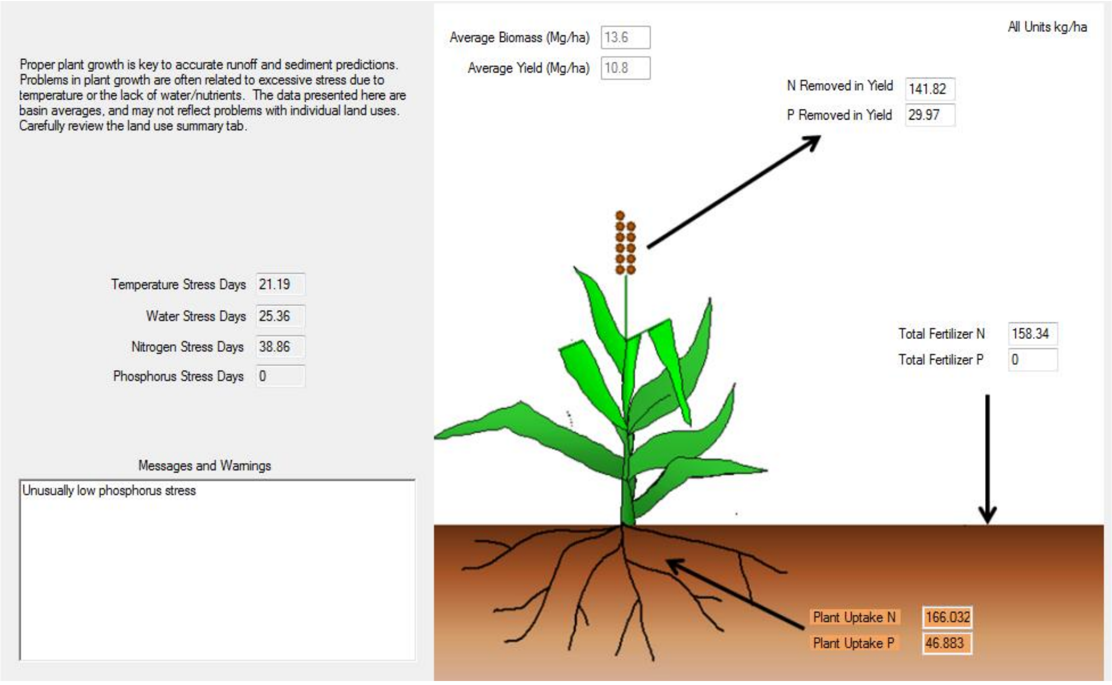
Average Biomass (Mg/ha) 12.3
Average Yield (Mg/ha) 9.5
All Units kg/ha
N Removed in Yield 142.86
P Removed in Yield 26.47
Temperature Stress Days 25.82
Water Stress Days 26.84
Nitrogen Stress Days 40.25
Phosphorus Stress Days 0.07
Total Fertilizer N 184.769
Total Fertilizer P 0

Messages and Warnings

Unusually low phosphorus stress

Plant Uptake N 202.856
Plant Uptake P 67.561

Fig. 7. Plant growth and Total NP under the actual observed scenario from 2005-2008 (SWAT, 2017)



Proper plant growth is key to accurate runoff and sediment predictions. Problems in plant growth are often related to excessive stress due to temperature or the lack of water/nutrients. The data presented here are basin averages, and may not reflect problems with individual land uses. Carefully review the land use summary tab.

Average Biomass (Mg/ha) 13.6
Average Yield (Mg/ha) 10.8
All Units kg/ha
N Removed in Yield 141.82
P Removed in Yield 29.97
Temperature Stress Days 21.19
Water Stress Days 25.36
Nitrogen Stress Days 38.86
Phosphorus Stress Days 0
Total Fertilizer N 158.34
Total Fertilizer P 0

Messages and Warnings

Unusually low phosphorus stress

Plant Uptake N 166.032
Plant Uptake P 46.883

Fig. 8. Plant growth and Total NP under the future climate change scenario by 2100 (SWAT, 2017)

4. CONCLUSION

This case study showed a decrease in streamflow of 3.53 to 3.48 mm from observed actual scenario (2005-2008) to projected increase of 4°C temperature in future climate change scenario by 2100. From the case study it is noticed that the evapotranspiration increased from 784.9 to 803 mm while there were no observed changes in precipitation. But there was a decrease in surface runoff from 195.6 to 189.44 mm and decrease in percolation likely occurred from 135.59 to 123.0 mm.

Moreover, there were greater average plant biomass from 12.3 to 13.6 kg/ha. Hence, more average plant yields from 9.5 to 10.8 kg/ha. With these, the nitrogen and phosphorus uptake and removal would lead to an increase in yield. Thus, the total nitrogen decreased from 184.7 to 158.3 kg/ha while the total phosphorus is zero indicating loss of the P content in the soil.

This indicates that the projected increase of 4°C temperature in future climate change scenario by 2100 favored increase in crop yields while limiting nitrogen and phosphorus levels at the White Oak Bayou watershed. However, this affects negatively the streamflow and other hydrological conditions such as evapotranspiration, surface runoff and percolation. While no changes observed with 2°C temperature increase for low emission scenario.

Yet, this case study needs to be validated and calibrated with actual data to support the projected outcome.

ACKNOWLEDGEMENT

The research is supported in part by the Erasmus Mundus Mobility with Asia Grant.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
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