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# **Application of the SWAT Model to assess climate change impacts on water balances and crop yields in the West Seti River Basin**

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## **Abstract**

*The West Seti River basin is located in the far western region of Nepal and has a catchment area of 7,438 km<sup>2</sup> and annual rainfall of approximately 1921 mm. According to Siddiqui et al., (2012) this basin is one of the most vulnerable in Nepal. The average elevation of the basin is 2505 m but can vary from 314 m to 7043 m in the Api and Nampa high mountain ranges. Agricultural land in this basin is categorized into three types: level terraces; slope terraces; and, valleys. The major summer cereal crops in the basin are rice, maize and millet and the major winter cereal crops are wheat and barley.*

*The Soil and Water Assessment Tool (SWAT) is used to simulate water balances in different cropping patterns under current and future climates. The results show that total precipitation over rice, maize, millet, wheat and barley fields are 1002 mm, 818 mm, 788 mm, 186 mm and 169 mm respectively whereas total simulated actual evapotranspiration (ET) are 534 mm, 452 mm, 322 mm, 138 mm and 177 mm respectively under current climate. Actual ET will change by +0.7% in rice, +3.4% in maize, -3.4% in millet, +41.2% in wheat and +36.2% in barley under future climate projections. Results show that yield of rice, maize and millet will decrease by 10%, 7.9% and 26.1% whereas yield of wheat and barley will increase by 7.8% and 5.8% respectively. Therefore, the impact of climate change shows that summer crop yields will decrease and winter crop yields will increase.*

**Key Words:** Water Balance, Hydrological Modeling, Climate Change, Crop Yields, SWAT

## Introduction

The Himalayan region is considered sensitive to climate change (CC), and developing countries, such as Nepal, are more vulnerable to CC because they have limited capacity to adapt to it (IPCC 2001). The Fourth Assessment of the Intergovernmental Panel on CC (IPCC 2007) states that due to increasing concentration of greenhouse gases in the atmosphere, a warming of about 0.2°C per decade is projected for the next two decades for a range of Special Report on Emissions Scenarios (SRES). The mountain regions of Nepal are the major source of water storage in the form of ice and snow. Between 1977 and 2000, the mean maximum temperature of Nepal increased by 0.06°C per year (Hua, 2009). The rise in temperature will affect the hydrological cycle, which in turn will have an impact on water availability, evapotranspiration, runoff and the discharge regime of rivers (Sayari et al., 2011).

Water has been identified as the key resource for development and economic growth of Nepal (WECS, 2011), therefore managing spatial and temporal water resources variability is critical in river basins that are vulnerable to climate change. In Nepal, most of the agricultural land in the hills and middle mountains depends on the rainfall and only few lands have irrigation access from local streams. The irrigation water management should be balanced with soil fertility management to increase the monsoonal crop yields and increasing soil fertility without considering the irrigation could result in crop failure (Shrestha et al., 2013). Consequently, agricultural production depends on the water availability in the local streams; and on the amount and timing of rainfall. Therefore, the central idea of this paper is to evaluate the impact of climate change on the soil water balance in the agricultural lands of the West Seti River sub-basins and subsequently to measure change in the yields of cereal crops. The spatially distributed agro-hydrological models are widely used to simulate hydrological parameters and crop yields in the river basin scale. Thus Soil and Water Assessment Tool (SWAT) is used to simulate water balance and crop yields in this study.

## **STUDY AREA: the West River Sub-basin**

According to a study on climate change vulnerability in the middle and high mountain regions of Nepal (Siddiqui et al., 2012), the West Seti sub-basin was identified as one of the most vulnerable sub-basins in relation to climate change. The West Seti River Sub-basin is located in the far western region of Nepal (Figure 1) and has a catchment area of 7,438 km<sup>2</sup> and has confluence point with the Karnali River as the basin outlet. The sub-basin originates from the snow fields and glaciers around the twin peaks of Api and Nampa in the south facing slopes of the main Himalayas. The average elevation of the sub-basin is 2505 m but it varies from 314 m at sub-basin outlet, to 7043 m of Api and Nampa high mountain ranges. The West Seti River is one of the major tributaries of Sapta Karnali River (the longest river of Nepal). In the period of 1981 to 2010, the average annual rainfall within the sub-basin was 1921 mm whereas seasonal precipitation was 137 mm in the winter; 261 mm in the pre-monsoon; 1449 mm in the monsoon; and, 74 mm in the post-monsoon seasons. Therefore, in this sub-basin almost 75% of annual rainfall occurred during the monsoon season. In the period 1981-2010, the daily maximum temperature varied from -17.3°C to +46.7°C and minimum temperature varied from -23.4°C to +31.3°C. The projected climate result shows that the average daily maximum temperature will change by -0.62°C to +0.66°C per decade and minimum temperature will change by -1.14°C to +0.03°C per decade in this study area. This shows an average day becomes hotter and night becomes colder.

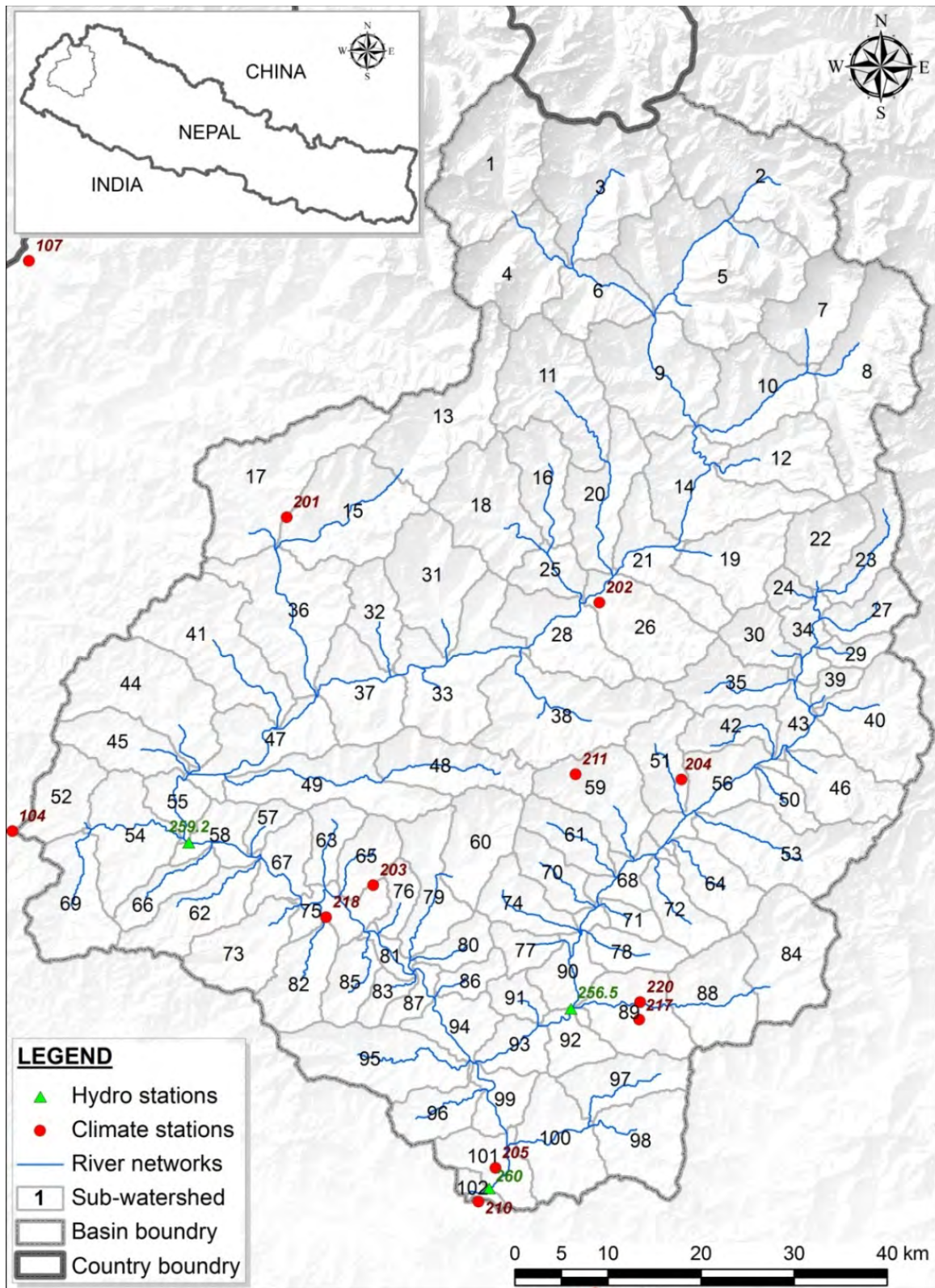


Figure 1: West Set River Sub-basin/Sub-watersheds with location of hydro meteorological stations

## **DATA AND SOURCES**

### ***Hydro-Meteorological Data***

SWAT requires time series of observed climate data i.e. rainfall, minimum and maximum temperature, solar radiation, wind speed and relative humidity. In this study, time series climate data from 1981 to 2010 from Department of Hydrology and Meteorological (DHM) of Nepal was used for model input. In addition, daily observed hydrological data obtained from DHM was used to calibrate and validate the model output. Altogether, data from 15 climate stations and 3 hydro stations was used for this study.

In this study, projected climate data from DHM (downscaled from PRECIS, and WRF regional climate models) were used to model future scenarios. The downscaled climate variables were based on the five global climate models (GCMs): ECHAM5, and HadCM3 in PRECIS; and, Era40, CCSM, ECHAM5, GFDL, and HadCM3 in WRF. The average of projected climate data from these seven projections, under A1B scenario, was used to assess climate change impacts. The projected climate time series data covered the periods from 1971 to 2000 as base line and 2031 to 2060 as the future projection.

### ***Spatial Data***

SWAT requires three basic files for delineating the basin into sub-basins and hydrologic response units: Digital Elevation Model (DEM); Soil map; and, Land Use/Land Cover (LULC) map. The Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2) with 1-arc second (approximately 30 m at the equator) resolution is used for the DEM in this study. This ASTER GDEM was jointly developed by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). The sources of the land cover map and soil map are from National Land Use Project (NLUP), Ministry of Land Reform and Management (MoLRM), Nepal.

### ***Agricultural Data***

Based on MoAC (2005), the crops considered in this study are: rice, maize, wheat, barley, millet, potato, oilseed, sugarcane and vegetables. Agricultural fields in level terraces are classified into

rice (19%), millet (16%), sugarcane (1%) and vegetables (64%) whereas agricultural fields in slope terraces are classified into maize (36%), oilseeds (6%), potato (8%) and vegetables (50%). All the agricultural fields in river valleys are classified as rice fields. Wheat and barley are considered as winter crops in rotation with summer crops such as rice, maize, millet, oilseeds and vegetables; whereas sugarcane and potato do not contain a second crop.

## METHODS

### *Soil and Water Assessment Tool (SWAT)*

SWAT is a process-based continuous hydrological model that predicts the impact of land management practices on water, sediment and agricultural chemical yields in complex sub-basins with varying soils, land use and management conditions (Arnold et al., 1998; Neitsch et al., 2011; Srinivasan et al., 1998). The main components of the model include: climate, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, and, channel and reservoir routing. Conceptually SWAT divides a basin into sub-basins. Each sub-basin is connected through a stream channel and further divided in to Hydrologic Response Unit (HRU). HRUs are a unique combination of a soil and a vegetation type in a sub watershed, and SWAT simulates hydrology, vegetation growth, and management practices at the HRU level.

The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^n (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

Where,

$SW_t$	:	Final soil water content (mm)
$SW_o$	:	Initial soil water content (mm)
$t$	:	Time (day)
$R_{day}$	:	Amount of precipitation on day $i$ (mm)
$Q_{surf}$	:	Amount of surface runoff on day $i$ (mm)



$E_a$  : Amount of actual evapotranspiration on day  $i$  (mm)

$w_{seep}$  : Amount of percolation on day  $i$  (mm)

$Q_{gw}$  : Amount of return flow on day  $i$  (mm)

Since the model maintains a continuous water balance, the subdivision of the basin enables the model to reflect differences in ET for various crops and soils. Thus, runoff is predicted separately for each sub-basin and routed to obtain the total runoff for the basin. This increases the accuracy and gives a much better physical description of the water balance. More detailed descriptions of the model can be found in Arnold et al. (2011) and Neitsch et al. (2011).

The SWAT model partitions crop yield from the total biomass on a daily basis (Arnold et al., 2011). The partitioning is based on the fraction of the above-ground plant dry biomass removed as dry economic yield and this fraction is known as harvest index (Neitsch et al., 2011). The harvest and kill operation is enabled to evaluate the crop yields in the modeling. The equations for the crop yield are;

$$YLD = bio_{ag} \times HI, \quad \text{when } HI \leq 1 \quad (2)$$

$$YLD = bio \times \left(1 - \frac{1}{1 + HI}\right), \quad \text{when } HI > 1 \quad (3)$$

Where,

$YLD$  = Crop yield (kg/ha),

$bio_{ag}$  = Above-ground biomass on the day of harvest (kg/ha),

$HI$  = Harvest index on the day of harvest, and

$bio$  = Total plant biomass on the day of harvest (kg/ha)

In this study, the harvest index considered for optimal growing conditions are: rice, 0.50; maize, 0.50; millet, 0.25; wheat, 0.40; and, barley, 0.54. Whereas the harvest index considered under highly stressed growing conditions are 0.25, 0.30, 0.10, 0.20, and 0.20 for rice, maize, millet, wheat and barley respectively. The potential harvest index for a given day is depend of the

harvest index for the plant at maturity given ideal growing conditions and the fraction of potential heat units accumulated for the plant (Neitsch et al., 2011). Thus SWAT takes into account the change in harvest index for the crops when there is water stress at certain phases of the crops. The equation for the actual harvest index in water stress condition is;

$$HI_{act} = (HI - HI_{min}) \frac{\gamma_{wu}}{\gamma_{wu} + \exp[6.13 - 0.883\gamma_{wu}]} + HI_{min} \quad (4)$$

$$\gamma_{wu} = 100 \frac{\sum_{i=1}^m E_a}{\sum_{i=1}^m E_o} \quad (5)$$

Where,

- $HI_{act}$  = Actual harvest index,
- $HI_{min}$  = Harvest index for the plant in drought conditions,
- $\gamma_{wu}$  = Water deficiency factor,
- $E_a$  = Amount of actual ET on day  $i$  (mm),
- $E_o$  = Amount of potential ET on day  $i$  (mm),
- $i$  = Day in the plant growing season, and
- $m$  = Day in harvest

### ***Model Calibration and Validation***

The stations and period considered for model calibration and validation are described in Table 1. The model performance is determined by Nash-Sutcliffe Efficiency (NSE) with respect to the daily and monthly observed flow data (Karki, 2012). The performance (Table 1) is acceptable as described by Liu and De Smedt (2004); and, Moriasi et al. (2007). Whereas, the simulated crop yields are not validated due to lack of data therefore only changes in crop yields are presented in this study.

Table 1: Hydrological Stations in the West Seti River Sub-basin and Model Performance (Karki, 2012)

Station	Period		Model Performance (%)			
	Calibration	Validation	Calibration		Validation	
			Daily	Monthly	Daily	Monthly
Budhi Ganga, Chitregat	2001-2003	2004-2006	73	90	60	78
Seti River, Gopaghat	1986-1990	1991-1995	67	86	54	90
West Seti, Banga	1981-1985	1986-1990	74	93	68	85

## RESULTS AND DISCUSSIONS

### *Trend of Actual Evapotranspiration (ET) and Crop Yields*

Figure 2 represents the correlation between simulated annual actual ET and crop yields for the period from 1981 to 2010. This study considers three scenarios of crop rotations in a year. They are;

- Rice-Wheat-Vegetables rotation scenario,
- Millet-Wheat rotation scenario, and
- Maize-Barley rotation scenario

The study shows a positive correlation between actual ET and crop yields however, the correlation coefficients are less than 0.50 in all crop rotation scenarios. In scenarios (a) and (b), crop yields gradually increase with respect to increase in actual ET. Linear trend lines show that the ratios of actual ET by crop yields are 0.95 and 0.84 in scenarios (a) and (b) respectively. In contrary, the scenario (c) shows crop yields increase slightly with respect to an abrupt increase in actual ET. Hence, the linear trend line shows that the ratio of actual ET by crop yields is 3.52 in scenario (c).

Figure 3 illustrates the trend of change in actual ET and crop yields under the selected crop rotation scenarios in the period from 1981 to 2010. Results show a declining trend of both actual ET and crop yields in the simulation period. The trend of changes in crop yields is following the trend of change in actual ET in all crop rotation scenarios.

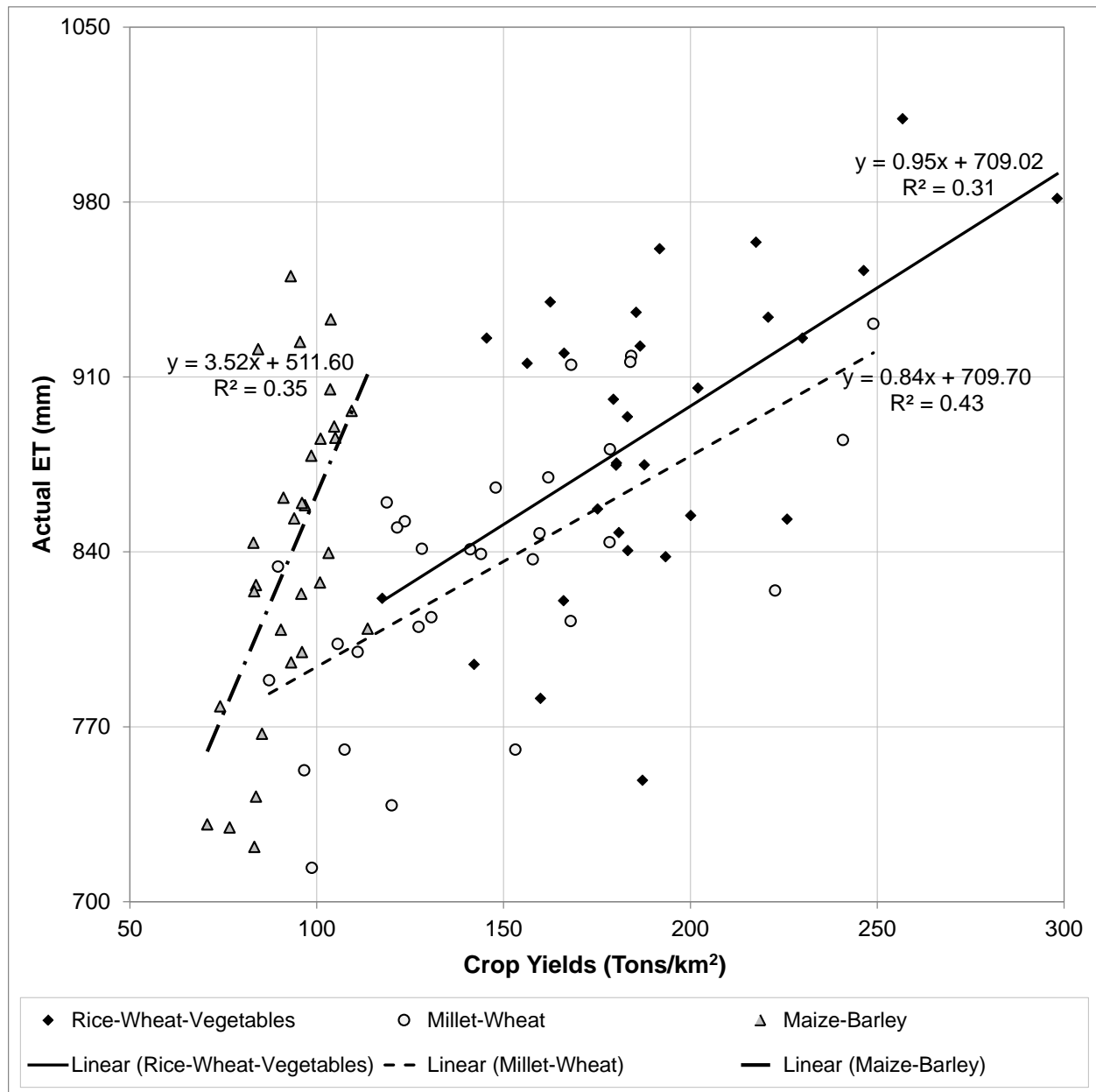


Figure 2: Correlation between Simulated Annual Actual Evapotranspiration (ET) and Crop Yields under Selected Crop Rotation Scenarios for 1981-2010 Periods

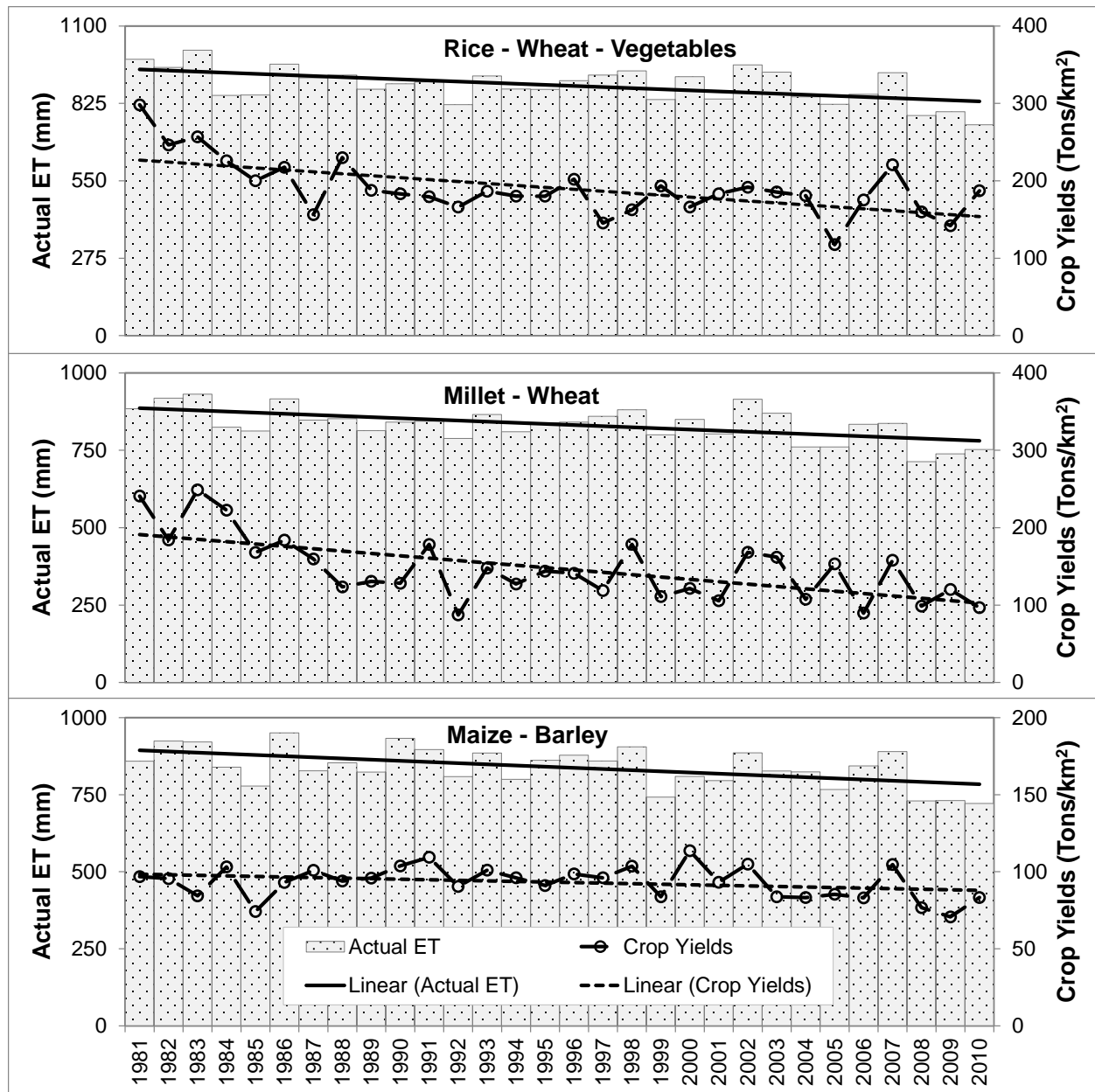


Figure 3: Actual Evapotranspiration (ET) and Crop Yields Trend under Selected Crop Rotation Scenarios for 1981-2010 Periods

### Water Balance and Crop Yields

As afore mentioned, the model runs from 1981 to 2010 with daily climate data and the outcome of this study represents average results over a 30 year period as a current climate scenario. The model result shows that total precipitation over rice, maize, millet, wheat and barley fields are 1002 mm, 818 mm, 788 mm, 186 mm and 169 mm respectively whereas total simulated actual

ET are 534 mm, 452 mm, 322 mm, 138 mm and 177 mm respectively under the current climate (Table 2). Similarly, simulated surface runoff from the crop fields and crop yields are presented in the Table 2. In the study, the total surface water yields are validated with the observed river flows however the simulated crop yields are not validated as there are no available data which spatially covers over the study area. All the crops are considered as rain-fed and the auto-irrigation option of model is enabled in the simulation. In auto-irrigation option, the model will automatically apply water up to a maximum amount whenever there is water stress in crops (Neitsch et al., 2011). Hence this study only looked into how climate change will impact on the crop yields with default parameters of the model and by auto-application of irrigation.

Table 2: Simulated Water Balance and Crop Yields under Current Climate

Variables	Summer Crop			Winter Crop	
	Rice	Maize	Millet	Wheat	Barley
Precipitation (mm)	1002	818	788	186	169
Actual ET (mm)	534	452	322	138	177
Surface Runoff (mm)	235	175	170	7	10
Crop Yields (Tons/km <sup>2</sup> )	54	83	15	45	29

### ***Impact of Climate Change on Water Balance and Crop Yields***

The climate change impact study is assessed by comparing between the model results of baseline (from 1971 to 2000) and future projections (from 2031 to 2060). The model results show that the total precipitation will change by -4.4% in rice, +0.5% in maize, -9.5% in millet, +37.3% in wheat, and +30.6% in barley fields. Similarly, actual ET will change by +0.7% in rice, +3.4% in maize, -3.4% in millet, +41.2% in wheat, and +36.2% in barley, under future climate projections. Actual ET will increase in all crops except in millet because water availability will decrease in the millet fields. The linear correlation will occur in the percentage change between precipitation and actual ET; and, between crops yield and actual ET (Figure 4). However, the correlation equations between actual ET and crop yields are different between summer and winter crop (Figure 4). The change in surface runoff on the crop fields is presented in the Table 3. Whereas the impact of climate change results show that crop yields from rice, maize and millet will decrease by 10%, 7.9% and 26.1% respectively, the yield of wheat and barley will increase by

7.8% and 5.8% respectively under future climate. The precipitation on the summer crops will decrease, except in maize which will impact negatively on the crop yields (Table 3). Whereas, precipitation on the winter crops will increase and this will lead to an increase in crop yields. Hence, the impact of climate change shows that summer crop yields will decrease and winter crop yields will increase. Therefore, the changes in amount of precipitation will impact on the actual ET, and then on the crop yields.

Table 3: Percentage Change in Simulated Water Balance and Crop Yields under Future Climate

Variables	Summer Crop			Winter Crop	
	Rice	Maize	Millet	Wheat	Barley
Precipitation	-4.4%	+0.5%	-9.5%	+37.3%	+30.6%
Actual ET	+0.7%	+3.4%	-3.4%	+41.2%	+36.2%
Surface Runoff	-12.6%	-6.3%	-16.9%	+21.9%	+18.1%
Crop Yields	-10.0%	-7.9%	-26.1%	+7.8%	+5.8%

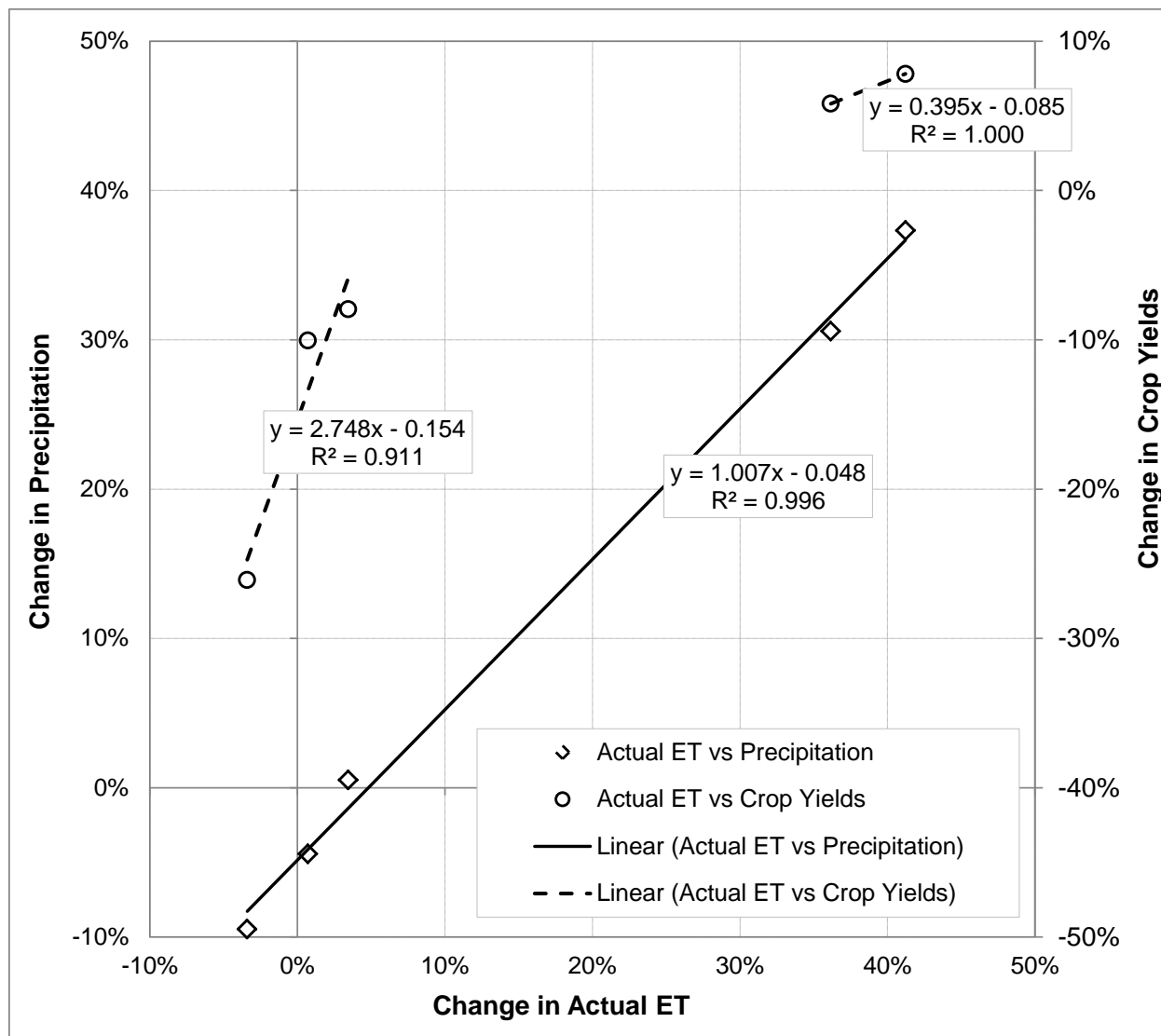


Figure 4: Correlation of Percentage Change between Precipitation and Actual ET, and between Crop Yields and Actual ET under Future Climate Scenario

## Conclusion

The result of the model simulation under current climate conditions shows declining trends of actual ET and crop yields in this study area. The projected model results show that summer precipitation will decrease except on the maize fields and winter precipitation will increase; whereas actual ET will increase for all crops except in millet under future climate scenario. As a result, summer crop yields will decrease and winter crop yields will increase under projected climate change scenarios. However, there is large degree of uncertainty in the simulated results



due to disagreement among the projected future climate scenarios (Bharati et al., 2012) and this uncertainty can reliably be reduced by using only a selection of GCMs that shows high inter-model similarity for the current and future climate (Sperna Weiland et al., 2012).

The SWAT model is found to be a good tool to simulate the water balances and crop yields under current and future climate scenarios. However, the model's performance will depend on the model inputs and availability of observed data to validate output. In this study, simulated water balance components are more precise due to the availability of observed river flow data. Whereas, due to unavailability of spatially coverage of crop yields data, the study is confident to present only changes in crop yields under future climate scenario.

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