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Adapting SWAT model for the evaluation of water harvesting systems in an arid environment: a case from Jordan

Lubna Al-Mahasneh*

National Center for Agricultural Research and Extension (NCARE), Research engineer, Amman, Jordan, Lmahasneh@ncare.gov.jo

Feras Ziadat

International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan, f.ziadat@cgiar.org

Raghavan Srinivasan

Spatial Science laboratory, Texas A&M University, Texas, Agricultural Experimental Station, College Station, Texas, USA, r-srinivasan@tamu.edu

Khaldoun Shatanawi

Assistant Professor, Civil Engineering Department, Faculty of Engineering and Technology, The University of Jordan, Amman, Jordan, kshatanawi@ju.edu.jo

Abstract:

Water scarcity and land degradation are widespread problems that affect agricultural productivity, food security and environmental quality in several parts of the world, particularly in the dry areas. Sustainable management of soil and water is necessary to optimize the use of limited rainwater for crop production and to decrease soil erosion. One management option is utilizing rainfall more efficiently through water harvesting. In arid areas, different types of water harvesting techniques (WHT) are being developed by researchers and used by farmers to utilize runoff water and to enhance plant growth. However, the effect of water harvesting on the reduction of soil erosion and runoff is not adequately known. This study aims at adapting the SWAT model to predict the impacts of selected water harvesting interventions on the bio-physical and hydrological processes and to evaluate their application in arid environments. Four sites, representing small sub-watersheds (hill slopes) were selected for modeling purposes in Al-Majidyya village 40 km south-east of Amman, which represents an arid area of Jordan (known locally as Al-Badia). The average annual rainfall in this area is less than 150 mm. Two small sub-watersheds (paired swales) were selected to measure runoff and *erosion, using flow meters and ISCO automatic samplers. One of these swales has been treated using Vallerani plough to form intermittent pits to collect and store runoff water. This swale was planted by Salsola vermiculata shrubs and the other swale has been left without any intervention (control representing the natural rangelands in the area). The other two small sub-watersheds (paired swales) were selected to measure sediment yield only using geo-textile trap. One of these paired swales contains continuous contour ridges as water harvesting measure and was planted with Atriplex halimus shrubs while the other sub-watershed was left without intervention and planted with Barley (Hordeum vulgare), representing the farmer practices. The model input parameters were derived using the SWAT ArcGIS Interface. Some parameters (Leaf Area Index and Harvest Index) for plant growth were modified to suit the prevailing arid conditions in the watersheds. Many iterations were carried out by introducing different management options in SWAT databases taking into account the subbasin, HRU and curve number values. The model overestimated the runoff and sediment yield from the water harvesting sites and to large extent accurately estimated for the sites without interventions. For example, the sediment yield predicted for the continuous contour ridges for a selected storm was 0.09 t/ha whereas no sediments were observed in the field. The predicted sediment yield for the barley site was 0.55 t/ha and the observed value was 0.34 t/ha. Manual calibration/comparisons for measured and observed results are needed to adapt the model for this arid environment and to accurately estimate the effect of water harvesting interventions. In addition the comparison of biomass and crop yield will also be analyzed between observed and SWAT predicted outputs.*

Keywords: soil and water losses, soil conservation, land degradation, rangelands

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Introduction

Accelerated soil erosion and water scarcity are widespread problems that affect agricultural productivity, food security and environmental quality in many countries of the world. Jordan is one of the countries that are suffering from water shortage and land degradation. Arid environments, such as Al-Badia, in Jordan are characterized by sporadic, low average annual rainfall and very high rainfall intensities that may cause runoff and erosion. Runoff causes erosion of the fertile topsoil which results in land degradation on site and increasing the risk of flooding towards the wadis.

Sustainable natural resources for both soil and water are required in order to optimize the benefit of available rainwater for crop production and to decrease the soil erosion and enhance soil fertility. Therefore, several types of water harvesting techniques (WHT) have been developed. For thousands of years, inhabitants of the dry areas have constructed water-harvesting systems that helped them cope with water scarcity (El Amami, 1984; Boers, 1994; Oweis et al., 2004) and support their livelihood.

The benefits of water harvesting in arid areas are not only to secure runoff water and recharge aquifers tapped for irrigation but also to increase crop production as well as decrease soil erosion. However, the effect of water harvesting on the reduction of soil erosion and runoff is not adequately known.

This study aims at adapting the SWAT model to predict the impacts of selected water harvesting interventions on the soil erosion and runoff. Therefore, the use of models to simulate the process at watershed scale has become a crucial and an important tool for estimating runoff and sediment yield and for quantifying the impacts of water harvesting interventions at various spatial and temporal scales. In this respect, SWAT (Soil and Water Assessment Tool) arises as a well-known useful model for quantifying soil erosion, sediment yield and runoff water (Arnold et al., 1998). Many studies that utilize SWAT to simulate soil erosion and sediment yield have been conducted. However; none specifically addressed the impact of water harvesting interventions in quantifying runoff and sediment yield. Therefore, SWAT is needed to simulate the spatial and temporal variation of runoff, sediments and productivity in arid watersheds and the impact of the implemented water-harvesting interventions.

Materials and Methods:

Study area description:

Four sites, representing small sub-watersheds (hill slopes) were selected for modeling purposes in Al-Majidyya village 40 km south-east of Amman, which represents an arid area of Jordan (known locally as Al-Badia, Figure1).

Two small sub-watersheds (paired swales) were selected to measure sediment yield only, using geo-textile trap (silt fences), which is a low-cost technique used to measure onsite hillslope erosion. Such a technique is easy to install by making the sediment trap face the upslope. The geotextile trap is folded to form a pocket for the sediment to settle on and reduce the possibility of sediment undermining. One of these paired swales (Contour Ridge site) contains continuous contour ridges as water harvesting measures and was planted with `Atriplex halimus shrubs, while the other sub-watershed (Barley site) was left as control site without intervention and planted with Barley (Hordeum vulgare), representing the farmer practices (Figure1).

The other two small sub-watersheds (paired swales) were selected to measure runoff and erosion, using flow meters and ISCO automatic samplers by establishing a weir as a control section at each outlet. One of these swales (Vallerani site) has been treated using Vallerani plough to form intermittent pits to collect and store runoff water. This swale was planted by Salsola vermiculata shrubs and the other swale has been left without any interventions (control representing the natural rangelands in the area). Each (paired swales) is located in close proximity to each other to minimize differences in climate, soils, vegetation, topography (elevation, aspect, and slope).

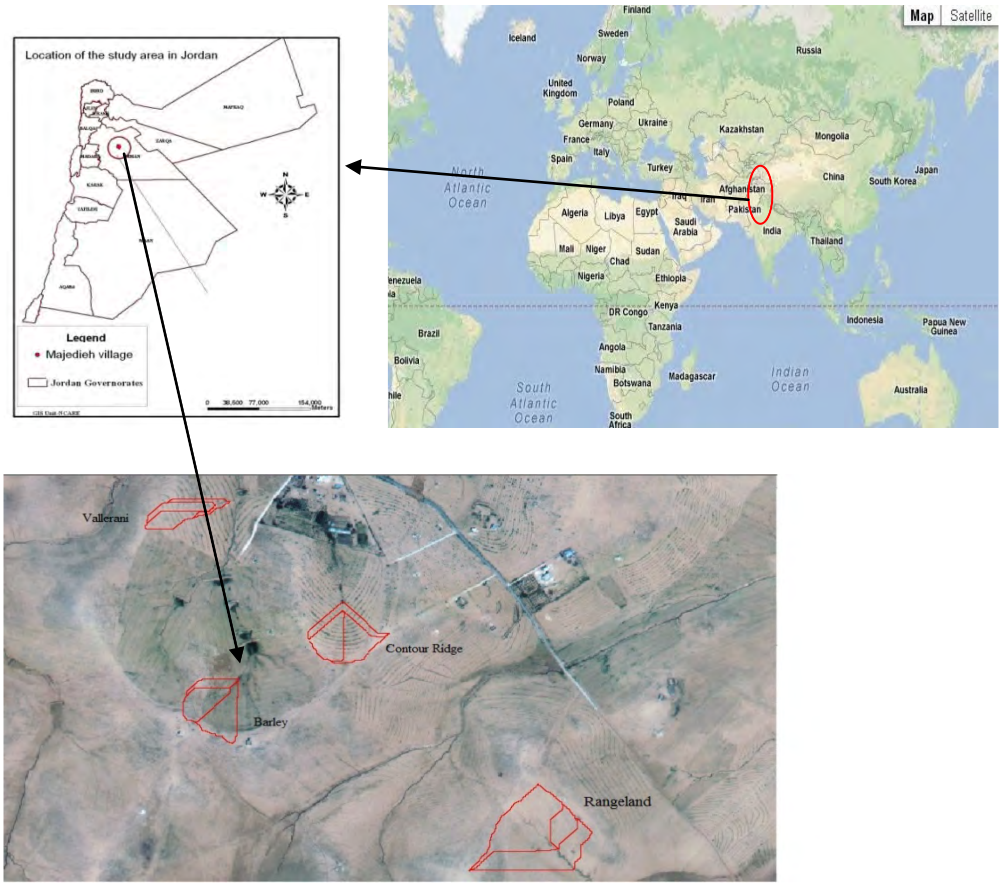

Figure 1: location of the study area in Jordan and four modeling watersheds that represent Al-Badia.

SWAT model:

Soil and Water Assessment Tool (SWAT) is a physically based continuous event watershed hydrologic simulator that estimates the impact of land management practices on surface and subsurface water movement, sediment, and agricultural chemical yields in large, complex watersheds with different soils, land use, and management conditions over 100 years of time (Arnold et al., 1998). The SWAT program is supported with an interface in ArcGIS (ARCSWAT 2009, Di Luzio et al., 2002) for the characterization of watershed hydrologic features and storage, as well as the organization and manipulation associated spatial and temporal data.

SWAT2012 version with its interface of ARCGIS 10.0 (Di Luzio et al., 2002) was used to execute this study.

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The basic data required to develop the model input parameters were: topography, soil, landuse and climatic data. The unique portion of the watershed determined by the hydrological response units (HRU) based on soil, landuse and slope in addition to physical processes and crops operations and management (irrigation, tillage, harvesting, and fertilizer). The model input information were prepared in the following pattern:

Catchment configurations: derivation of DEM (Digital Elevation Model) was extracted using ArcGIS for each site by the information provided from the executed topographic survey using total station at 50 cm resolution.

Soil map: Sampling grids were taken for each soil observation location using Global Positioning Systems (GPS). A bio-physical characterization surveys were conducted for each observation location based on the soil data collection form. Soil Samples for surface and subsurface at each observation location were taken for physical and chemical Laboratory analyses. Some of physiochemical soil properties were measured such as bulk density, organic matter, stone content and texture, and some of soil parameters were estimated such as hydraulic conductivity, available water holding capacity using soil parameters estimate (SOILPAR v2.00) and the other soil parameters were estimated from input/output documentation of SWAT model such as erodibility K factor and Albedo. Soil map was produced with Thiessen polygon method with unique name using ArcGIS. A user soil database was developed with all relevant soil parameters required to input to SWAT2012.

Landuse map: Recent and high resolution satellite imagery for the site (type world view 60 cm, spring 2011) was used for identifying and digitizing the existing landuse/landcover classes using ArcGIS. The classes of landuse were those that are used by SWAT model with some modification for selected landuse classes. As a result, new SWAT landuse codes were created in term of changing the parameters of plant growth and other conditions that may characterize the sites.

Climate data: historic records for the metrological data (rainfall, temperature, solar radiation, relative humidity/or dew point, wind speed) from Queen Alia International

Airport station and Muaqqer station that belongs to the University of Jordan are the nearest stations of the sites which were used to run the weather generator file. In addition to an automatic rain gage was installed in the site to measure the rainfall intensities during the rainy seasons.

Hydrological and sediment data:

The required information of eroded sediment yields on the geotextile traps was estimated. In addition, to the information and samples of generated runoff at the weirs edge were recorded using flow meter probes and ISCO automatic samplers. Moreover, the rainfall intensities from rain gauge were used.

Results and discussion:

Sediment yield prediction using SWAT:

This presented study focuses to discuss the application of SWAT model to study the impact of water harvesting interventions on the soil erosion. SWAT utilizes the Modified Universal Soil Loss Equation (MUSLE) to estimate soil losses. This equation developed by Williams (1975) uses the amount of runoff generated in each HRU to simulate sediment yield for each HRU in each sub basin. Then, they are added to compute the contribution of sediment yield for whole basin. As a result, sediment yield predictions are improved, the accuracy of the prediction is increased and sediment yields on individual rainfall events (storms) can be estimated (Neitsch et al., 2002). The SWAT model was simulated to the site implemented by continuous contour ridges and the control site without water harvesting intervention. The model outputs determined daily and monthly sediment yields (kg/ha) based on some modifications that suit the existing arid conditions in both sites.

The application of the SWAT in arid regions requires modifications of the existing SWAT databases and parameters. Therefore the existing land cover/plant parameters are not suitable for arid environment in Al-Badia of Jordan conditions. One of the limitations, in this study, was the little or no data or available literature for the crops planted in the study area (Atriplex, Salsola shrubs and winter barley). Another challenge was how to

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consider the continuous contour ridges as certain type of water harvesting interventions (Figure 2) implemented in the site. This consideration was involved in both model setup and simulation processes. Also, this challenge not only to consider it as soil conservation management practices but also as intervention measures that optimize the benefit of the rain water and increase plant productivity and reduce soil erosion.

Figure 2: Continuous contour ridges as one type of the water harvesting interventions implemented in the site.

The measured data from the field for sediment yields for the site implemented by water harvesting interventions type continuous contour ridges were totally different for the control site

The traditional procedure adopted by farmers in the control site in plantation and management of winter barley usually contributes to the soil erosion. The land is tilled in up and down slopes. This way makes the soil very loose and become weak especially that the soil texture in the site contains a high percent of silt. As a result, the traditional farmer practices contribute in a direct way to the sediment amounts transported and eroded on the site, where also the amount and pattern of rainfall intensity in that area can easily washe off the top soil and nutrients which is cause soil erosion by water (Figure 3).

Figure 3: control site planted by Barley as farmer practices and the problem of soil erosion and transported sediment yields at the geotextile traps.

As a result, one of the considerations is including the established contour ridges planted with Atriplex in the produced HRUs by adding a new landuse class and modifying the crop database which contains SWAT plant growth parameters. Therefore, new SWAT landuse codes were created with the appropriate modifications (contour ridges and barely). The modified parameters are Harvest Index (HVI), Leaf Area Index (LAI) parameters and identifying the landuse conditions that affect the Curve number values corresponding to each hydrological soil group in the basin for both sites. In addition to modifying the management and operations for each site. The operations are the plant/begin growing season, harvest and kill and applying fertilizers. Change the heat units' parameter according to the management type and existing operation for each landuse class for each site as summarized in the Table (1).

Furthermore, the physical processes were considered in the model setup and in the SWAT management practices options for selected produced HRUs in the basin for each site.

Table1: Some parameters values changed in the SWAT landuse code*

Site	Parameter	
	HVI	LAI
Continuous Contour Ridges	0.9	1.5
Winter Barley	0.54	4

(* these values were modified by Dr. Srinivasan, R., April,2012)

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Simulation of the SWAT model periods was identified. The whole period was Nov. 2005 to Dec. 2012. A period of 2005 till 2010 was used to warm up the model. However, Two years of measured data for soil erosion were collected during winter seasons of Nov. 2011/ May 2012 and Nov. 2012/ May 2013. Furthermore, these will be used for calibration and verification the model outputs.

Figure (4) illustrates the obtained results without calibration. It is shown that the magnitude and temporal variation of simulated monthly sediment yield for the selected storms in January does not match the observed sediment loads. Timings of occurrence of the peaks for observed and simulated sediment yield as well. However, they look in the same pattern but the model over-predicted sediment amounts during the January 2012 and it was also over estimated some peak values except the storm happened at December 2012. Although, the simulated and observed are closely match in magnitude and temporal variations at the end of the season in March 2012, Unlike, the contour ridges site that contains a (Continuous Contour Ridges as certain type of water harvesting measures), no sediments were observed in the field during all storms within the same period. But the model simulation output without calibration for monthly sediment yield was over estimated as illustrated the in figure (5) comparing with the measured one. The model with this result maybe requires fine-tuning to the input model parameters to include the established continuous contour ridges as water harvesting interventions in the site and its impacts that reduce the soil erosion. So, calibration and verification analysis is required.

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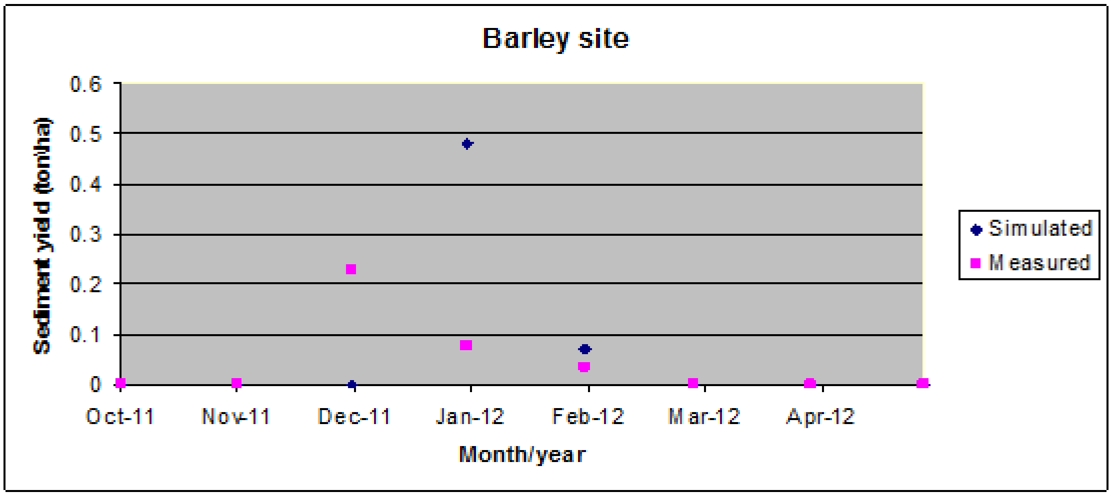

Figure 4: comparison of sediment yields (ton/ha) between SWAT simulation output and measured in the field for barley site.

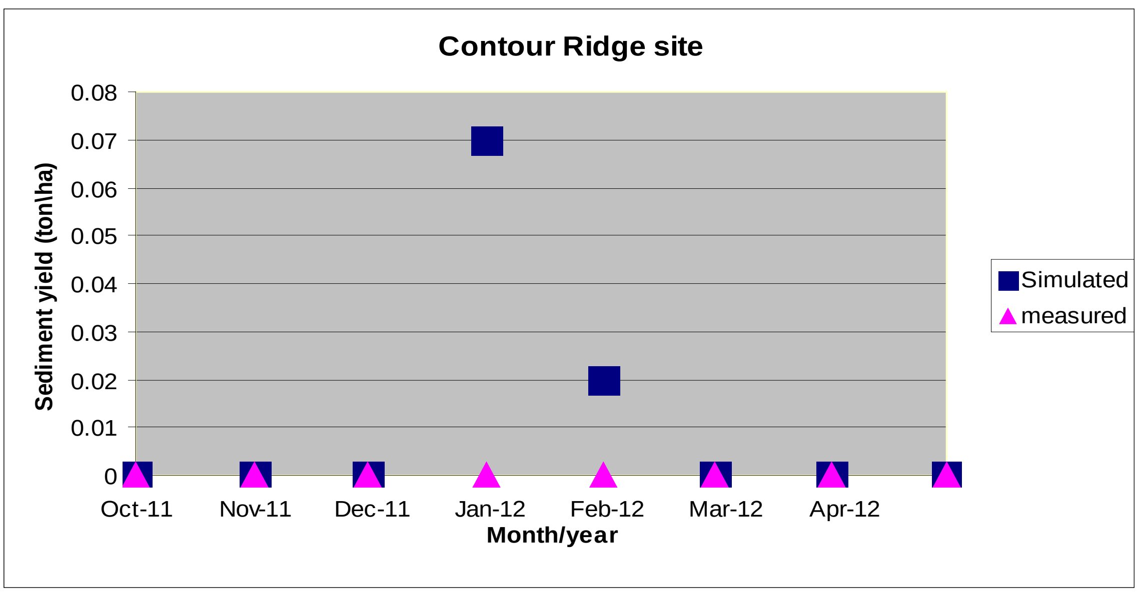

Figure 5: comparison of sediment yields (ton/ha) between SWAT simulation output and measured in the field for Continuous Contour Ridges site.

Biomass predictions using SWAT:

The SWAT model was used to simulate total biomass yield throughout barley, contour ridges and vallerani sites. The parameters which affect the biomass production are Leaf Area Index (LAI), soil evaporation and evapotranspiration. LAI values is estimated for each HRU by changing some plant growth parameters build in the model to suit existing condition in the study area. So the LAI was changed as mentioned in Table1. SWAT calculates the potential growth of plant for each day of simulation as a function of energy where the plant intercepts the efficiency of its conversion into biomass. Actual growth and actual LAI are dependent on stress factors like water, temperatures and nutrients. Optimal leaf area index is related with crop stage which in turn depends on the crop heat units. These heat units are defined in the SWAT database for each crop. The SWAT model was used to simulate total biomass yield. The model is under predicted the biomass production for the sites implemented by water harvesting interventions. In the contrast, the model is well matched with measured by assumption of applying fertilizers of 10 k/ha N for barley site (Figure 6).

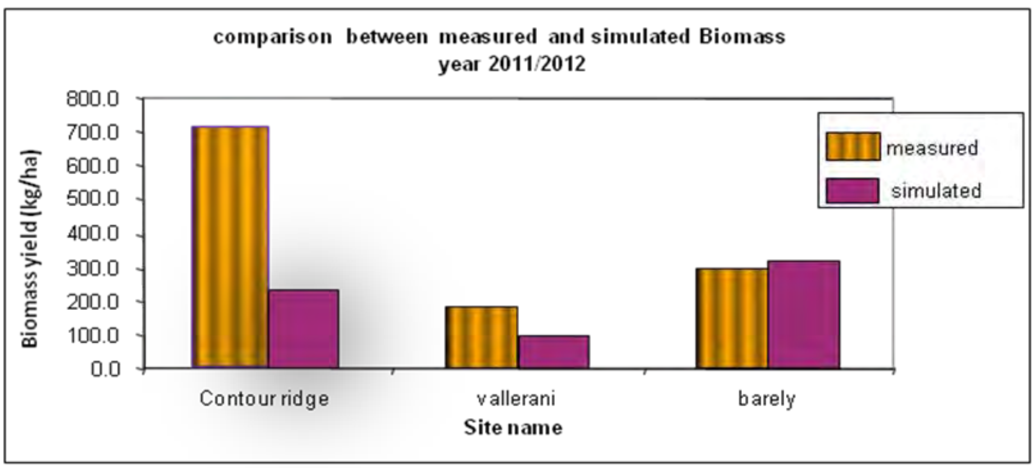

Figure 6: comparison between measured and simulated biomass for the sites.

Figure 7 illustrates that different scenarios were applied to the barley site that assume applying of the natural and chemical fertilizers will improve the crop biomass and yields

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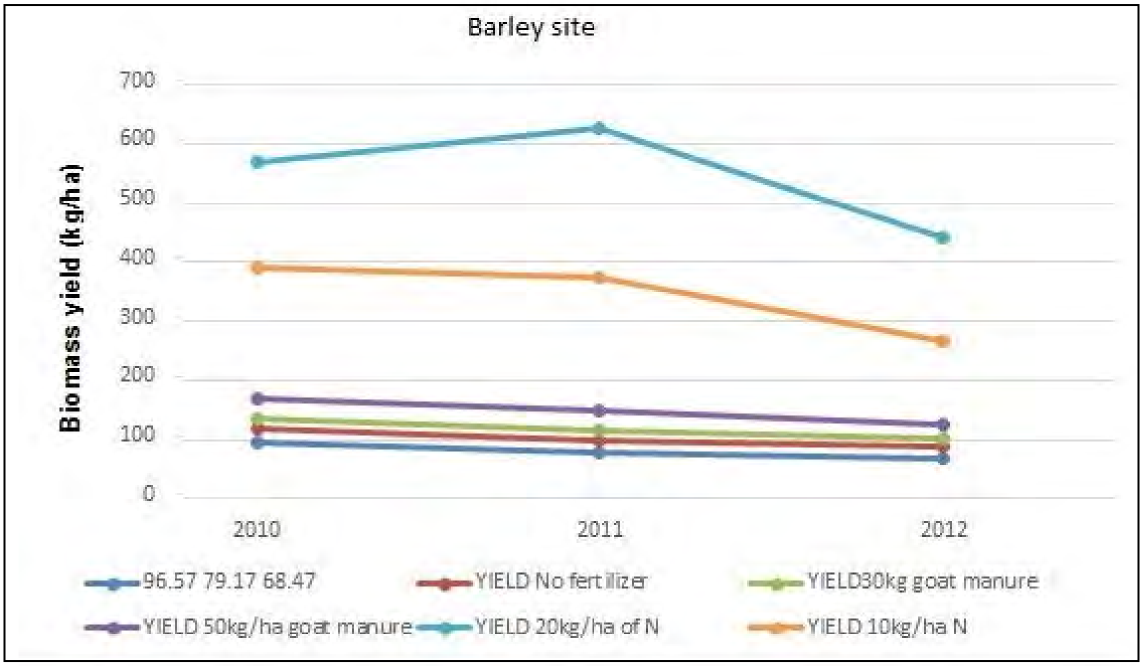

Figure 7: comparison of different scenarios applied to the barley site for the model biomass outputs. (Source: Dr. Srinivasan, R., April, 2012)

Conclusions:

This study focuses on simulation of SWAT model to predict the sediment yields for the sites that measure the soil erosion only. These are barley and contour ridges. In addition to simulate the model to predict the biomass productions for the sites of Barley, Contour ridges and Vallerani. The most important input data include meteorology, topography, soil data, landuse, water harvesting interventions and the applied agricultural practices. This study modeled the sediment yield from the site implemented by contour ridges water harvesting interventions and control site for the rainy season of 2011/2012.

SWAT outputs were evaluated by comparing simulated sediment yields with the measured sediment loads from the two sites.

Soil erosion from watersheds contributes a large amount of top soil and nutrients each year. The measured data presents evidence that the water harvesting interventions

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reduce the soil erosion and can aid in reducing losses and thereby have the potential to optimize the benefit of rainfall especially in the arid environment.

The biomass results can be significant for the farmers to adopt the water harvesting interventions which maximize the productivity.

References

Journal article

Bingner, R. L., Garbrecht, J., Arnold, J. G., and Srinivasan, R.: Effect of watershed division on simulation of runoff and fine sediment yield, *Transactions of the American Society of Civil Engineers, 40(5), 1329–1335.*

Ouessar M., Sghaier M., Mahdhi N., Abdelli F., De graaff J., Cchaieb H., Yahyaoui H. and Gabriel D. (2004). An integrated approach for impact assessment of water harvesting techniques in dry areas: the case of oued oum zessar watershed (Tunisia). Environmental Monitoring and Assessment (99) : 127–140.

Ouessar, M., Bruggeman A., Abdelli, F., Mohtar, R. H., Gabriels D., and Cornelis, W. M. (2008). Modelling water-harvesting systems in the arid south of Tunisia using SWAT. Hydrology and Earth System Sciences Discussions, (5), 1863–1902.

Robichaud, P.R.; McCool, D.K.; Pannkuk, C.D.; Brown, R.E.; Mutch, P.W. 2001. Trap Efficiency of Silt Fences Used in Hillslope Erosion Studies. Soil erosion for the 21st century: proceedings of the international symposium. St. Joseph, MI: ASAE. 541-543. ASAE Pub. No. 701P0007.

Hessel, R. and Tenge, A. (2008). A pragmatic approach to modelling soil and water conservation measures with a catchment scale erosion model. CATENA, 74(2), 119-126.

Robichaud, Peter R.; Brown, Robert E. 2002. Silt fences: an economical technique for measuring hillslope soil erosion. Gen. Tech. Rep. RMRS-GTR-94. 24 p.

Published paper

Almeida, C., Chambel-Leitao, P. Jauch, E. And Neves. R.(2011)SWAT LAI calibration with local LAI measurements. : Proceedings, 2011 International SWAT Conference. June15-17, 2011. University of Castilla La Mancha at Toledo, Spain.

Guevara, B., Casanova, M. and Ramos, M. 2011. Soil erosion modelling in agro-forested catchment of NE Spain affected by gullying using SWAT: Proceedings, 2011 International SWAT Conference. June15-17, 2011. University of Castilla La Mancha at Toledo, Spain.

Kuwajima, J., Crestano, S., Zuquette, L., Mauad, F.)2011). Challenges and difficulties in sediment modeling applied to sedimentation study of the Lobo reservoir in Brazil. : Proceedings, 2011 International SWAT Conference. June15-17, 2011. University of Castilla La Mancha at Toledo, Spain.

Oweis, T., D. Prinz and A. Hachum. 2001. Water Harvesting: Indigenous Knowledge for the Future of the Drier Environments. ICARDA, Aleppo, Syria. 40 pages.

Tue, V., Srinivasan, R., Shie-Yui, L. and Adri, V. 2011. Quantifying SWAT runoff using grided observations and reanalysis data for Dakbla river basin, Vietnam. : Proceedings, 2011 International SWAT Conference. June15-17, 2011. University of Castilla La Mancha at Toledo, Spain.

Dissertation or thesis

Ziadat, F. (1995). Effect of management practices on soil losses in arid to semi arid area in Jordan. Unpublished Ms Dissertation. University of Jordan.