Assessment of Crop Water Productivity using SWAT model in Sathanur Reservoir Catchment, India

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ABSTRACT

Globally, agriculture accounts for 80–90% of all freshwater used by humans and most of that is in crop production. In future less water will be available for agricultural production due to competition with the industrial and domestic sectors, while at the same time food production must be increased to feed the growing population. As the agricultural sector is considered to be the largest water user, faces a challenge to produce more food with less water. This requires an increase in crop water productivity (CWP) which can be defined as the ratio of "crop yield to evapotranspiration". Improving water productivity is an important approach to achieve global food security.

India is mainly depending on agriculture for their livelihood, but the increasing population and overexploitation of surface and groundwater over the past few decades has resulted in water scarcity for agricultural activities. Rice, wheat, maize and sugarcane are used as agricultural crops in India and most of them are water-consuming crops. CWP is a function of many factors like the water vapour pressure deficit of the atmosphere, soil fertility, irrigation. Any management factors that increase crop yield also increase CWP.

The present study focuses on assessing Crop Water Productivity in Sathanur catchment using SWAT (Soil and Water Assessment Tool) model. SWAT is a watershed model, in order to estimate the CWP in the catchment area SWAT is a sophisticated model. Crop yield is to maximize by fulfilling the crop water demand after meeting ET. The ET minimizes the growth and yield of crop by absorbing the water from crop. SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. It is a physically based continuous time model and semi distributed parameter model based on a daily scale.

Potential Evapotranspiration (PET) will be estimated by Penman - Monteith method whereas the crop yield obtained from the product of Harvest Index (HI) and Biomass of the plant. Then the model Calibration and validation using observed values (Observed ET and Crop yield) are done. From the estimation of water availability and water demand for crop, the suggestions will be given to the farmers about release of water for irrigation. Finally, from the SWAT model a spatial mapping of Agricultural Water Productivity for the watershed will be produced and the results helped in expanding the field scale into regional scale.

1. INTRODUCTION

Water is one of the most important things on earth. Every living thing needs water for its survival. Without water, plants, animals, microbes – everything will expire. Basically all human uses require fresh water. The total volume of water on Earth is about 1.4 billion km^3 (UNEP). India is the second most populated country in the world. But the increasing population and overexploitation of surface and groundwater over the past few decades has resulted in water scarcity in some regions. The main occupation in India is Agriculture, around 3,000 litres of water is converted from liquid to vapour, to produce enough food to satisfy one person's daily dietary need. Rice, wheat, maize and sugarcane are used as agricultural crops in India and most of them are water-consuming crops.

The impact of climate change presents extraordinary challenges for users and managers of water resources. Water scarcity is particularly acute in many developing countries, which have to cope with rapidly expanding populations, and the need to eradicate poverty and improve people's quality of life. In the Sathanur Reservoir Catchment, agriculture is the largest consumer of water. Therefore, any appropriate strategies for water savings and more efficient use of water in agriculture would help to mange water scarcity issues in the catchment. The production of more food under a water-scarce situation can be achieved by maximizing crop yield per unit of water consumed which is termed "crop water productivity". (Kaushal K.Garg *et al., 2012).*

The Sathanur reservoir catchment is very complex with highly spatial and temporal variability in climate, water availability, land use, irrigation practices and soil type. There is a need for analytical tools or models that can simulate the basin hydrology, land use and provide site-specific interventions. The Soil and Water Assessment Tool (SWAT) (Arnold *et al., 1998)* is a process-based continuous hydrological model that can predict the impact of land management practices spatio-temporally on water and agricultural yields in complex watersheds with varying soils, land use and management conditions. Several researchers have successfully used the model for hydrological and water resources assessment. In particular (Immmerzeel *et al., 2008)* have used SWAT to map WP in the Upper Bhima Basin which was calibrated by using remotely sensed evapotranspiration based on the SEBAL algorithm.

The present study aims at mapping agricultural Water Productivity within the basin using actual observations (evapotranspiration and crop yield) for calibration.

2. LITERATURE REVIEW

The following literature which has been reviewed in order to carried out the work and the papers related to Crop yield, Evapotranspiration and assessment of crop water productivity using SWAT model. (Monireh Faramarzi et al*.,* 2010) modeled irrigated and rain fed wheat yield and consumptive water use with uncertainty analysis at a sub basin level in Iran. Simulated yield and ET were used to calculate CWP. An analysis of Yield-CWP relationship showed that one unit increase in rain fed wheat yield resulted in a lesser additional Water requirement than irrigated wheat, leading to a larger improvement in CWP. The model was calibrated and validated against crop yield and ET. The SUFI-2 program in the SWAT-CUP package was used for uncertainty analysis. The crop yields were simulated with ET values of less than 200mm.The limitation in the crop yield simulation are as always related to the lack of information like planting and harvest dates, dates of irrigation and pesticide applications, and also consideration of seed variety, which is usually missing from the analysis.

(Kaushal K.Garg et al*.,* 2012) have carried out a study to assess CWP from the hydrological processes using SWAT in the Upper Bhima River Basin. The model was calibrated by using remotely sensed evapotranspiration based on the SEBAL (Surface Energy Balance Algorithm for Land). The four scenario analysis has been done with an aim to improve Economic Water Productivity (EWP) and mapped for various years (wet, normal and dry rainfall years). Crop productivity was found in the lower range when compared with potential and global values. High nutrient losses in upstream locations due to heavy runoff and inefficient water utilization in water-rich command areas are other important factors for poor Water Productivity.

(Geethalakshmi et al., 2011) have carried out a study to understand the variations in hydrology and rice crop productivity during different observed ENSO in the Cauvery river basin of Tamil Nadu, India using SWAT. Validation of SWAT model showed that the model predicted rice productivity close to the observed data under normal situations compared to the extreme weather conditions such as drought and flood. The coefficient of variation in rice productivity was higher during La-Nina years compared to El-Nino and Normal years. The mean rice productivity was shifted up in both El-Nino and Normal years indicating the possibility of getting higher yields compared to La -Nina years. Analysis of hydrological data and rice productivity indicated that the risk of failure was much lesser during the El-Nino years compared to normal or La-Nina years.

The authors (Feng Huang and Li Baoguo 2010) have carried out a study to assess CWP on staple grain crops which is associated with green water and blue water consumption in the Breadbasket Basins of China. Here the AET was calculated using SWAT. A GIS-based spatial aggregation and disaggregation method was developed to group the regional statistics to basin level. The calculated CWPs were also validated by comparing with the results; the results showed that CWPs were within a reasonable range. They concluded that to increase water productivity through research innovation and technological upgrading at river basin scale, which is a key to mitigating water stress arising from additional crop production. The water required for crop production will definitely increase in the years to come.

(Immerzeel et al., 2008) have carried out a study to assess the Water use and CWP in the Upper Bhima catchment using an innovative integration of remotely sensed ET and a process-based hydrological model. The model was calibrated used to derive a monthly basin water balance and then assessed the CWP and crop water use. They concluded that the frequency distributions of CWP has low coefficient of variation and limited yield for the current cropping systems. Hence the improvements in water productivity may be able to be achieved by shifting the crop base.

(Baskaran et al., 2010) modeled production of switch grass and river flow using SWAT in Arkansas-White-Red river basin. The lowland switch grass yields simulated by SWAT was compared with empirical data and also compared monthly SWAT flow predictions to USGS measurements from 86 sub basins across the region. After calibration, the functional validation was carried out against monthly Steam flow and yields. The SWAT Model yields being lower than the empirical model yields. The Differences between the empirical model and SWAT model Results were compared. POLYSYS is an economic model used to estimate where switchgrass could help to replace other land uses based on relative economic profit. Here they suggest that to include reservoirs losses to irrigation and evaporation which might be improve the simulation of seasonal flow patterns.

Another study have carried out for the evaluation of Hydrologic Budget and Crop yield simulations without calibration using SWAT model in the Upper Mississippi River Basin by (Srinivasan et al, 2010). The major hydrological budget components that were evaluated in this study are AET, soil moisture storage, and stream flow. The uncalibrated SWAT model predicted the stream flow and crop yield with observed data. The SWAT model estimated crop yield at 20% moisture content during harvest time and the Model captured the amount and variability of annual stream flow very well, PBIAS is less than 10% for 11 monitoring stations, r^2 values range between 0.78 and 0.99, and NSE (Nash – Sutcliffe Efficiency) ranges between 0.51 and 0.95. For monthly stream flow simulation, the performance of SWAT is slightly degraded r^2 values range from 0.10 to 0.80, and NSE ranges between 0.29 and 0.81 results was compared with calibrated SWAT model result.

(Lakshmanan et al., 2011) used SWAT model to assess the impacts of climate change on hydrology and rice yield in the Bhavani Basin of India. Climate change scenarios were developed using the RegCM3 model with EH5OM GCM (General Circulation Model) output for an A1B scenario, and generated daily climate data were used in the SWAT model. To validate the SWAT model, predicted rice yields for the Bhavani Basin over a period of 11 years were compared with the observed rice yields of Erode district in which the Bhavani Basin is located and the results indicated the satisfactory performance of the model. The SWAT model can be employed under different climate change and management scenarios for developing adaptation strategies to sustain rice production. The SRI (System Rice Intensification) system of rice cultivation is found to be a better adaptive technology for changing climatic conditions than the conventional flooding system of cultivation.

(Luo Yi et al., 2008) have carried out a study to assess the performance of the plant–soil–groundwater modules and the variability and transferability of SWAT2000. It was an experimental study conducted at the Yucheng Comprehensive Experimental Station (YCES) of the Chinese Academy of Sciences at Yucheng City. The data collected from the experimental station like weather data, crop parameters, soil data, Groundwater data, these parameters were incorporated into the model and the model was run. The simulated results by SWAT to the observations showed that SWAT performed quite unsatisfactorily in LAI (Leaf Area Index) predictions during the senescence stage, in yield predictions, and in soil-water estimation under dry soil-profile conditions. This is due to improper computation of Harvest Index (HI) and LAI. This version had some limitations, When SWAT used for agricultural watershed; the model parameters are important to calibrate the model against the field data. From this some improvements is to be needed in the future versions of SWAT. It should be carefully designed, so that it will give more accurate result in the estimation of crop growth parameters.

(Wang et al., 2006) have carried out a study to test the three PET (Potential Evapotranspiration) methods within SWAT's framework using the data collected from the Wild Rice River watershed, located in North-western Minnesota. The performance of the SWAT model was measured using three statistics: the Nash-Sutcliffe coefficient, coefficient of determination and performance virtue. The use of the three PET methods resulted in different values for two calibration parameters, namely the soil evaporation compensation factor and SCS curve number. The results indicated that after calibration, using the three PET methods within SWAT produced very similar hydrologic predictions for the study watershed.

(Si Gou et al., 2009) have carried out a study to calculate yearly average ET of different land use types and different regions in Tianjin by two methods, remote sensing inversion and SWAT model simulation. The SWAT model was also used to simulate the ET for dominating crops in Tianjin. While comparing the results of the two methods, the deviation is over 22%. The results of ET from SWAT model simulation are larger than the ET results of remote sensing inversion. The result of SWAT model should also be validated by local experiment results. The evaporation from soil and transpiration of wheat and corn during their growing period was calculated, and it was found that soil evaporation makes up 43% of the total ET during wheat's growing period.

(Weib and Menzel 2008) have carried out a study to compare the four different PET equations (Priestley Taylor, Kimberly Penman, Penman Monteith and Hargreaves method) on a global basis to demonstrate their difference, and assess their impact on the calculation of stream flows. Due to the limited availability of data, they found it difficult to assess which method was the physically most reasonable one to be applied. According to this study, the radiation-based Priestley Taylor equation was proved to be most suitable for global application. For the calculation of stream flows, however, the processes involved in the derivation of AET (Actual Evapotranspiration) values from PET values appear more relevant than the absolute value of the potential evapotranspiration itself.

3. SITE DESCRIPTION

The Sathanur Reservoir Catchment (Figure 1) is one of the main tributaries of the Pennaiyar river with a catchment area of 10 835 km^2. The Sathanur Reservoir Project (SRP) is constructed across the river Ponnaiyar in reserve forest area near Sathanur village. It is situated from the Thiruvannamalai town at longitude 78° 51' 10" and latitude 12° 4' 48". It was built with a storage capacity of 229M.cu.m. However the present capacity is 207 M.cu.m including dead storage 9 M.cu.m. There is a pick-up-anicut at 7.2 km. downstream from the dam from where irrigation use begins and (Figure 2) shows the location of major reservoirs, stream network, rainfall and meteorological stations in Sathanur Reservoir Catchment.

The major area of the catchment is relatively flat and it is about 75%. The climate of the catchment lies within the tropical monsoon. Based on the hydro-meteorological features of the basin, year is divided into 2 periods i.e. Monsoon period spanning from June to December and Non-monsoon period spanning from January to May. The monsoon period is further sub-divided into Southwest monsoon period spanning from June to September (4 months) and Northeast monsoon period spanning from October to December (3 months). Similarly, the non-monsoon period is further sub-divided into winter period spanning January and February (2 months) and summer period spanning from March to May (3 months). As the monsoon period brings heavy rainfall, it improves the recharging of groundwater as well as storage of surface water. Hence, the monsoon period is significant for water resources analysis in aspect of hydrology. But in the case of non-monsoon, it is insignificant. The mean annual rainfall of the catchment is 1000 mm, with an uneven distribution in space and time. The mean maximum temperature varies from 29.5^{0}C to 38.5^{0}C in May and minimum temperature varies from 20.4^{0}C to 26.5^{0}C in January. Soil in the catchment is broadly divided into three groups: clay loam, loamy and clay.

Inflow takes place during the monsoon season and the stored water is supplied for irrigation and non-irrigation uses throughout the year depending upon the water availability in a reservoir. The land use consists of rainfed and irrigated area, forest, rangeland and water bodies (Figure 3 and Table I). About 63% of total land is under agriculture, with 35% forest. The crops grown in this basin are Coconut, Banana, Fruits, Paddy, Vegetables, Chillies, Blackgram, Greengram, Groundnut, Gingelly, Cumbu, Ragi, Cotton, Cholam, Turmeric, Sugarcane, Flowers.

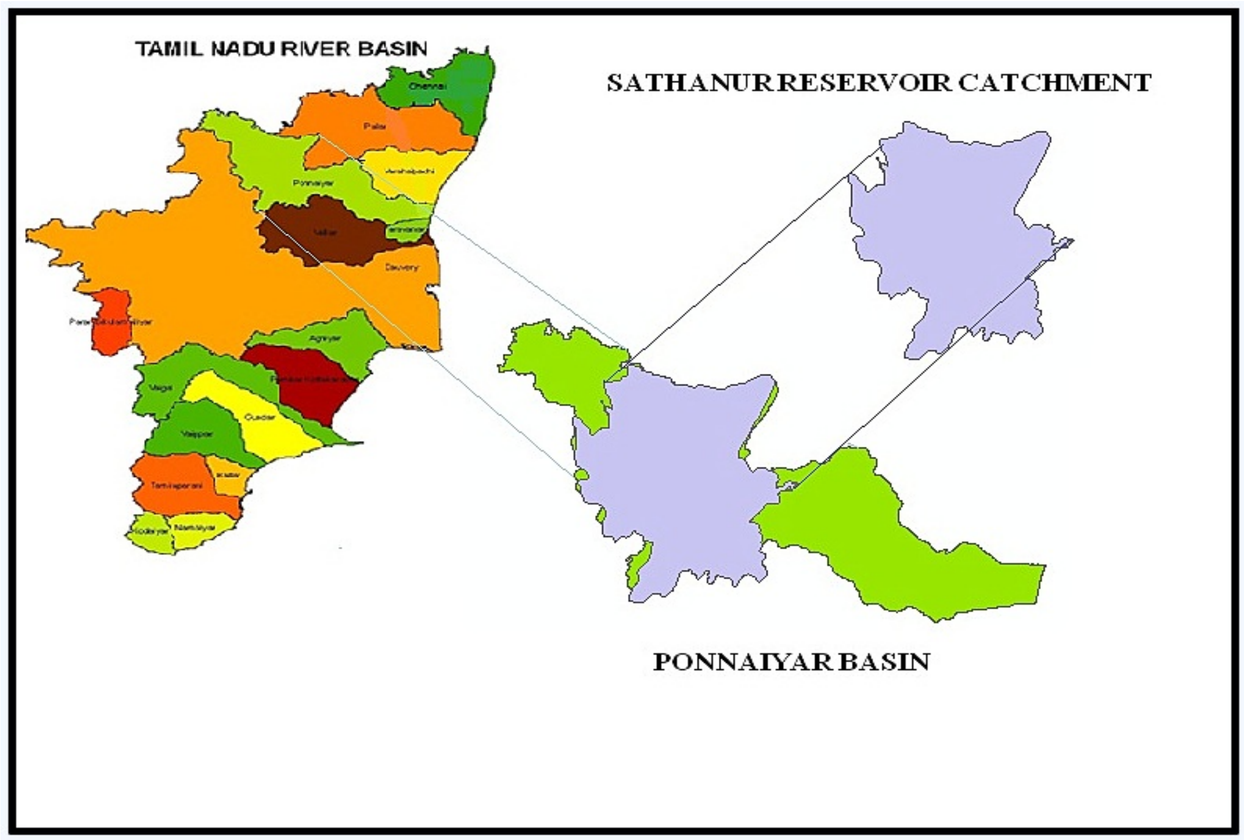

Figure 1. Index Map Of Sathanur Reservoir Catchment

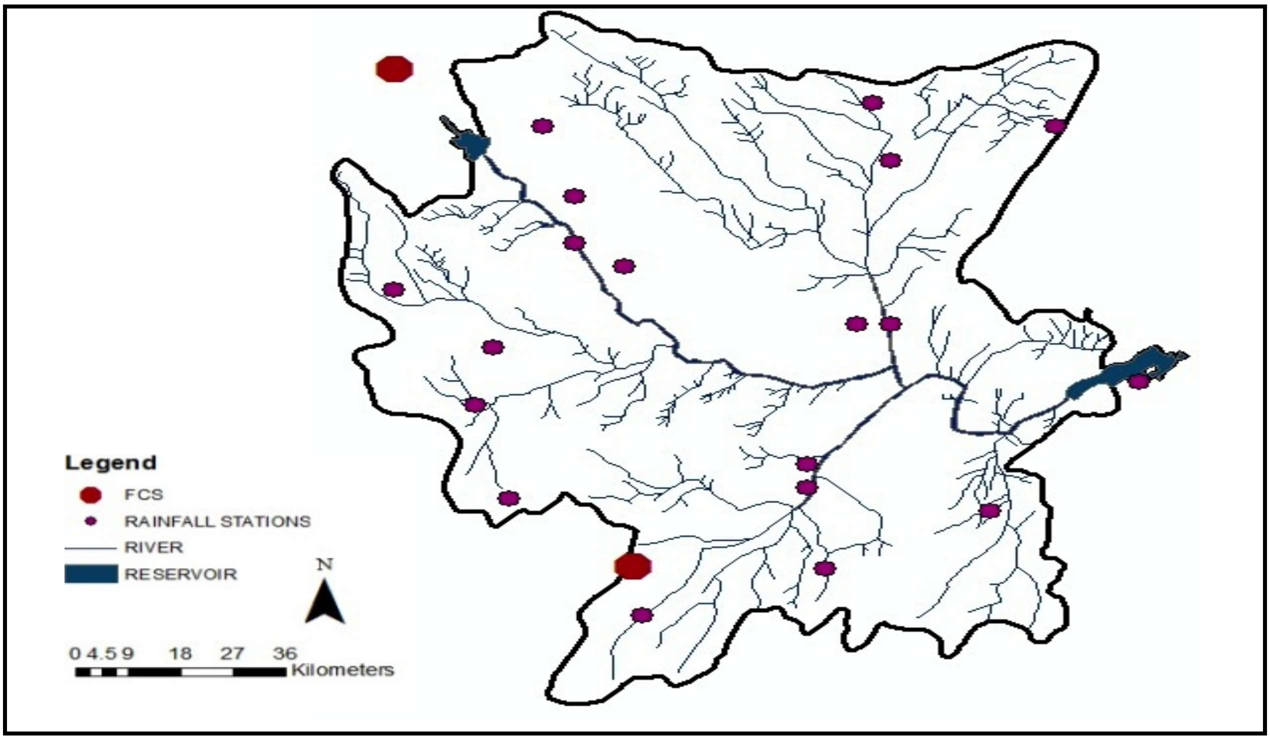

Figure 2. Location of major reservoirs, stream network, rainfall and meteorological stations in Sathanur Reservoir Catchment

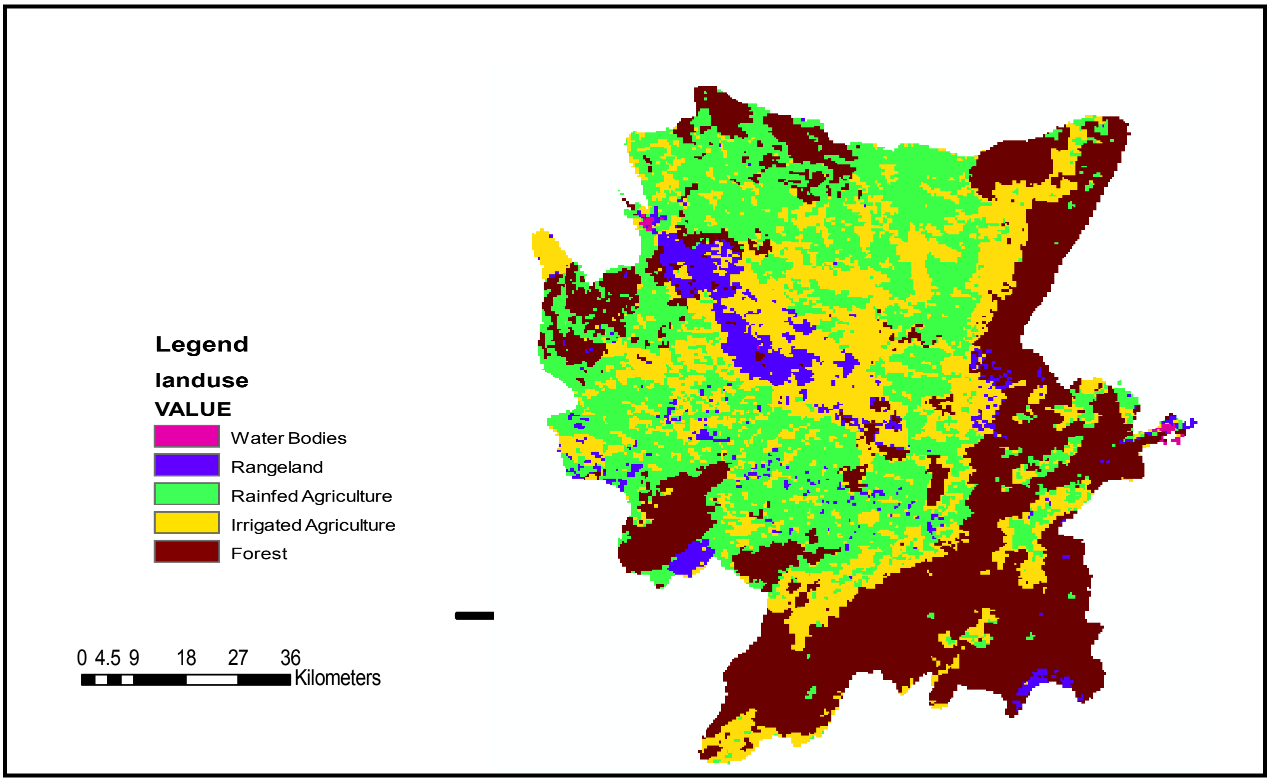

Figure 3. Major Land use classes in Sathanur Reservoir Catchment

Table I. Land use Classes in Sathanur Reservoir Catchment

Sl.No	Classification	Area (km^2)	Percentage (%)
1	Agricultural	3200.23	58.52
2	Built – up land	1162.26	2.12
3	Forest	1550.45	28.35
4	Wastelands	433.09	7.92
5	Water	168.14	3.07

4. METHODOLOGY

SWAT model is adopted to estimate the Crop yield and potential evapotranspiration. (Figure 4) shows the detailed methodology which helps to carried out the study.

4.1 SWAT MODEL SET-UP

The Soil and Water Assessment Tool (SWAT) is a process-based continuous hydrological model and the main components of the model include: climate, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, channel and reservoir routing. The public domain model ArcSWAT2012 working with the ArcGIS10 interface was selected for this study as it considers spatial variability of soil, land use, climate and also captures human-induced land and water management practices which is particularly important in a complex basin like the Sathanur Reservoir Catchment.

The model divides the watershed into multiple sub basins, which are then further sub-divided into hydrological response units (HRUs) which consist of homogeneous land use, management and soil characteristics. SWAT divides rainfall into different components which include evaporation, surface runoff, infiltration, plant uptake, lateral flow and groundwater recharge. Surface runoff from daily rainfall is estimated with a modification of the SCS curve number method from the United States Department of Agriculture Soil Conservation Service (USDA SCS) and peak runoff rates using a modified rational method (Neitsch et al., 2005). The model estimates plant growth under optimal conditions, and then computes the actual growth under stresses inferred by water and nutrient deficiency.

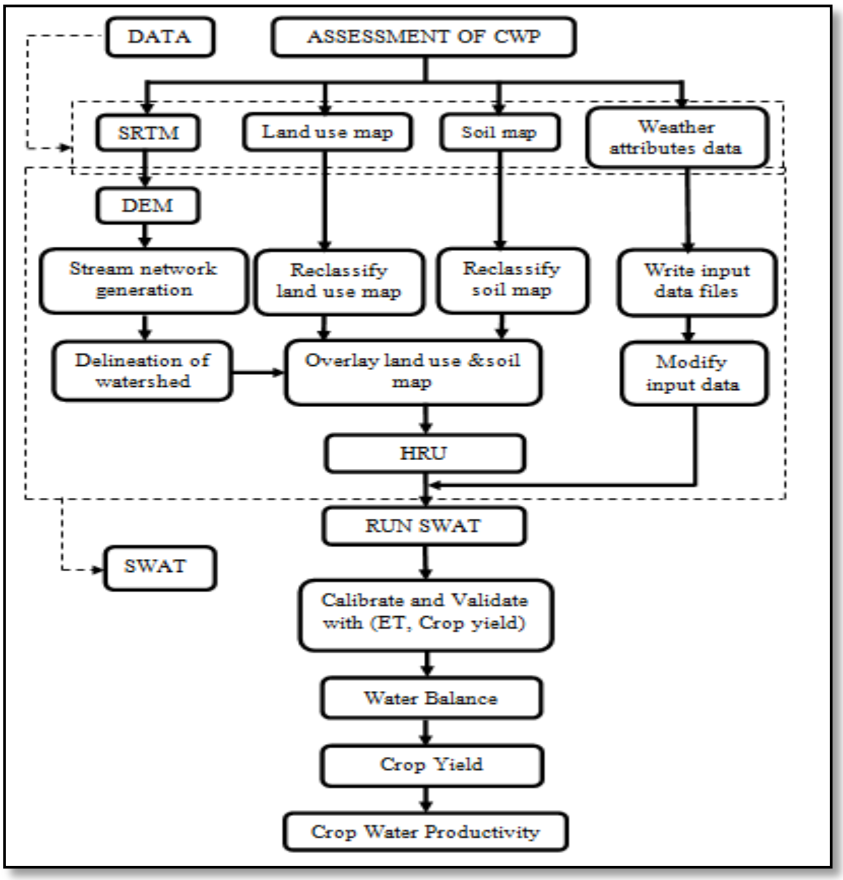

Figure 4. Methodology Flowchart

SWAT requires three basic files for delineating the basin into sub□basins and HRUs: a digital elevation model (DEM), soil map and land use/land cover (LULC) map. A 90m spatial resolution shuttle radar topographic mission (SRTM) DEM was used in this analysis. A soil map and Land use map of India state was collected from the Open source. Later, these classes were attributed to the six main classes (Figure 3)

Daily rainfall data from 22 rain gauge stations (Figure 2), which are spatially spread across the entire catchment, were collected from the Statistical Department of Tamilnadu, Chennai, India. Further records of meteorological parameters such as daily maximum and minimum temperatures, wind speed, solar radiation and relative humidity were obtained from the Data Centre in Chennai, India. Daily evaporation data also collected from the Data Centre Chennai, Tamilnadu, for model calibration and validation purposes. Similarly, daily inflow and outflow data of different reservoirs were collected from the Public Works Department of Krishnagiri and Sathanur, Tamilnadu, India. The sub-district-level data for cropping pattern and crop yield data were collected from the Agricultural Statistics Department of Tamilnadu for the entire Catchment.

A total of 23 sub-basins and 758 HRUs (Figure 5) were delineated in the Sathanur Reservoir Catchment and SWAT attributes like Soil, management and hydrological parameters for each HRU will be given as input data. Reservoirs play an important role in the hydrology of the Sathanur Reservoir Catchment. Therefore 2 reservoirs were built into the model to represent the total storage in the basin. The threshold value for the creation of HRU is chosen as 0% of land use, 5% of soil and 5% of slope.

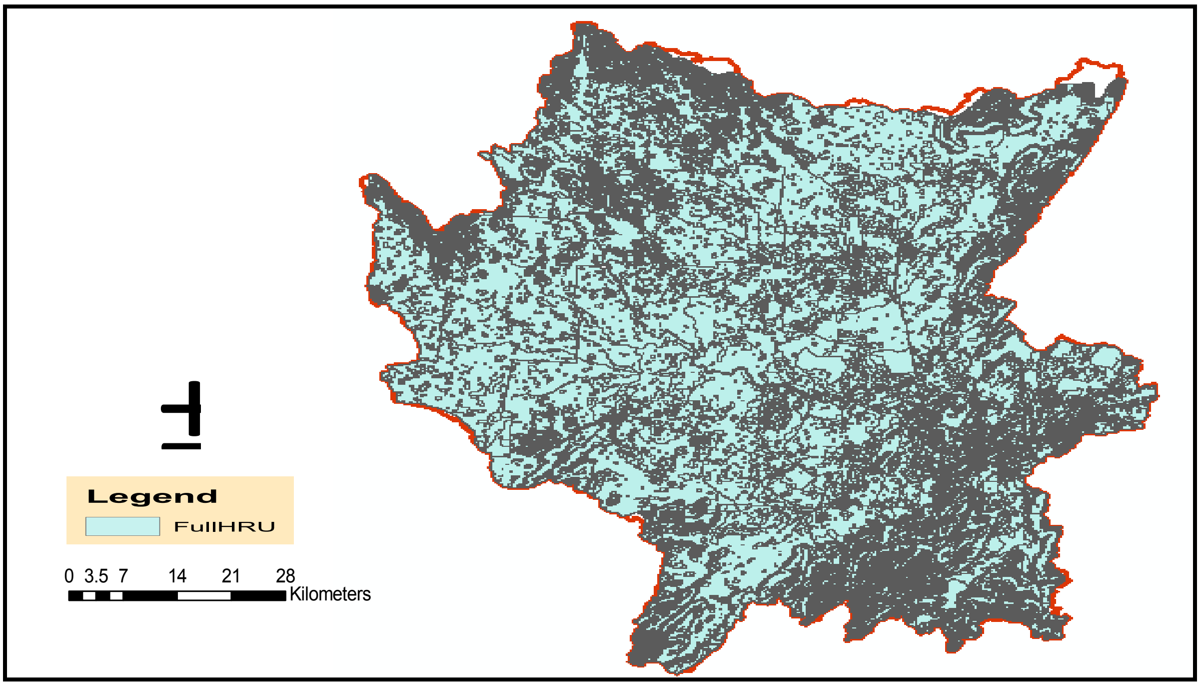

Figure 5. Hydrological Response Units for Sathanur Reservoir Catchment

5. MODEL CALIBRATION AND VALIDATION

The data from January 2006 to December 2008 will be used for model calibration, data from January 2009 to December 2010 for model validation. In the calibration phase, evapotranspiration will be simulated at a daily time step and compared with observed values. In addition, SWAT simulated values of Crop yield also compare with observed values during the calibration process.

As if it is not feasible to include all parameters in the calibration procedure, sensitivity analysis will be performed for a few locations. Performance evaluation of the model will be assessed based on the Nash–Sutcliffe efficiency coefficient (NSE) and the correlation coefficient (r) as well as visual comparison of hydrographs. Moreover, crop growth parameters for different crops will be adjusted by Comparing simulated and measured crop yield in rainfed and irrigated locations.

6. ESTIMATION OF CROP WATER PRODUCTIVITY

Crop WP is the amount of grain yield obtained per unit of water used (Tuong and Bouman, 2003). Depending on the type of water sources considered, WP is expressed as grain yield per unit water evapotranspired (WPET) or grain yield per unit total water input (irrigation plus rainfall) (WPIP). In this study, technical WP will be calculated using simulated values of evapotranspiration (ETa) and yield values of different crops over the entire catchment area.

6. RESULTS AND DISCUSSIONS

A total of 23 sub-basins and 758 HRUs were delineated in the Sathanur Reservoir Catchment. Performance evaluation of the model will be assessed based on the Nash–Sutcliffe efficiency (NSE) coefficient and the correlation coefficient (r) as well as visual comparison of hydrographs. Positive values of NSE indicate that the calibrated model was a better predictor than the mean values of the observed values. Spatial distribution of ETa and Crop yield Will be analyzed and represented as maps using SWAT.

7. SUMMARY AND CONCLUSION

The Sathanur Reservoir Catchment is facing water shortages due to intensive development in domestic and irrigation water needs. In this study, the hydrological processes of the Sathanur Reservoir Catchment were modeled using the distributed hydrologic model, SWAT. The spatial pattern of WP of major crops will be analyzed with the aim of improving water use efficiency in the irrigated area.

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