

Impacts of climate change on water provisional services in Tungabhadra basin using InVEST Model

Vijaykumar Bejagam¹, Venkata Reddy Keesara², and Venkataramana Sridhar^{3*}

¹Post Graduate Student, Department of Civil Engineering, National Institute of Technology Warangal, Telangana-506004, India. Email: vbejagam@student.nitw.ac.in

²Associate Professor, Department of Civil Engineering, National Institute of Technology Warangal, Telangana-506004, India, Email: kvreddy@nitw.ac.in

³Associate Professor, Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA.

Email: vsri@vt.edu; * corresponding author

Abstract

Water is one of the most important ecosystem services because it is essential for food and energy production. The Tungabhadra basin, located in peninsular India, has a variety of challenges, including inter-basin water-sharing issues, low agricultural productivity and value, and rising need for renewable energy production. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) water yield model is used to analyze the consequences of climate change on water related services such as water yield and hydropower generation in the densely populated Tungabhadra basin. The impact of climate change on water supply services is studied for the period 1971-2000 as well as the future period 2021-2040. The model is calibrated using streamflow data collected at the Bawapuram gauge station in Telangana and there is a strong correlation between observed and simulated flow. The water yield for the entire basin declined by 33 and 50 percent under the Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios, respectively. The RCP 4.5 scenario reduces hydropower production and its Net Present Value (NPV) by 41 to 59 percent, whereas the RCP 8.5 scenario reduces production and NPV by 56 to 67 percent. The assessment of ecosystem services at the catchment scale revealed that the basin could be vulnerable to climate change due to a dramatic drop in ecosystem services. The methodology developed in this study can be applied to other river basins where quantifying ecosystem services is critical.

1. INTRODUCTION

Climate change is the most important, and undoubtedly the most complicated, vulnerable, and worldwide environmental concern to date, and it has a direct impact on water availability and related services (Kandlikar and Sagar 1999). Climate change and its variability will have a major impact on the region's water resources (Dibike and Coulibaly 2005). Climate change study is required to determine its effects on many aspects of water resource availability (Jayanthi and Keesara 2019). Climate change has a negative impact on water-related ecosystem services in most countries. (Bangash et al. 2013). In India, rainfall is distributed unevenly, with the northeastern region receiving the most (Goyal and Surampalli 2018). Chaturvedi et al. (2012) analyzed data on multi-model with multi-scenario precipitation and temperature projections in India and determined that India's temperature anomaly will range from 1.7 °C to 2.0 °C by 2030s, with a mean precipitation change of 1.2 % to 2.4 %.

The complex cycle of water, food, and energy is referred to as the water-food-energy nexus (Endo et al. 2017; Smajgl et al. 2016). The population is rapidly growing, necessitating increases in food production, water needs for agriculture, and energy generation (Karabulut et al. 2016). Water is required for food production, while energy is required for food processing and preservation (Allan et al. 2015). Water is required to generate energy, and energy is utilized to pump water (Li et al. 2021). Because of these food-energy-water systems interdependencies, understanding the nexus is critical for sustainable development (Naderi et al. 2021). The ecosystem is central because it involves food, water and energy production (Bennett et al. 2021). The sources and sinks of fluxes are constantly modulated through streamflow, soil moisture, evapotranspiration, and aquifers, and several studies have investigated these partitioning of land surface fluxes (Sridhar and Wedin, 2009; Sridhar et al., 2018), but direct linking of hydrological processes with ecosystems is largely limited. While hydrologic extremes such as drought, landslides and anthropogenic-induced land use change, degrade ecosystems, there is renewed interest to evaluate the ecosystem services when the functioning of these ecosystems is hampered (Sehgal and Sridhar, 2019; Kang and Sridhar, 2019; Sridhar et al., 2019; Sujatha and Sridhar, 2018; Seong et al., 2018). Ecosystem services are called

the benefits human beings gain from the ecosystem (Duku et al. 2015; Francesconi et al. 2016; Nelson and Daily 2010). Four different types of ecosystem services are provisional, regulatory, cultural and supportive services (Fisher et al. 2009; Wagstaff and Wortman 1999; Wallace 2007). Provisioning services are the direct needs of an ecosystem (e.g., food, water, timber, and fiber), regulating services are from ecosystem process regulation (e.g., water, climate, disease, and pest regulation) (Klein et al. 2007), cultural services are other than material benefits people obtain from an ecosystem (e.g., aesthetic values, recreation, ecotourism, and cultural diversity) and supporting services are those services which make the ecosystem to continue to provide services (soil formation, pollination, etc.) (Adhikari and Hartemink 2016; Fisher and Kerry Turner 2008). The effort to manage these ecosystem services has increased because of its recognized social value (Yang et al. 2019). Water-related ecosystems (rivers, lakes, groundwater) support critical ecosystem services for human and animal life such as water yield, fish production, recreation, and hydropower power generation (Grizzetti et al. 2016). Bangash et al. (2013) studied the climate change impact on ecosystem services in the Mediterranean River basin, and found the basin highly susceptible to climate change. Karabulut et al. (2016) developed an integrated framework for the evaluation of the Danube Basin provisional water services. Sahle et al. (2019) quantified and mapped water provisional and soil regulating services in the Omo-Gibe basin.

In future, the climate change scenarios for the Krishna basin are predicted to suffer from severe drought (Goasin et al. 2018). Increased greenhouse gas emissions have an impact on hydrological events in the Krishna basin by raising global temperatures, modifying rainfall patterns, evapotranspiration, soil moisture, streamflow, and the severity of floods and droughts (Tirupathi et al. 2020). Because climate change impacts are region-specific, dry and semi-arid regions are more vulnerable (Al-Hasan and Mattar 2014). Rainfall and temperature patterns are predicted to be drastically altered as a result of climate change, affecting the availability of water for food and energy production in the Tungabhadra basin, a tributary of the Krishna River (ACIWRM and WRD 2012). In the Tungabhadra sub-basin, a trend analysis based on Sen's estimator for annual and monsoon rainfall revealed a negative and declining trend (Harshavardhan et al. 2020). The need for energy in developing countries can be met by increasing hydropower production and development

(Fu et al. 2014). In India, agriculture/irrigation accounts for roughly 80% of total water consumption and 30% of total electricity consumption (Malik 2002). Changes in stream flow and variations in energy prices have a negative influence on hydropower plant revenue (Green et al. 2015). Because this basin has water-sharing concerns and relies heavily on agriculture, mapping water-related ecosystem services is critical. Therefore, the mapping and analysis of provisional water services like water yield and hydropower production in the Tungabhadra Basin is assessed in this study.

There are different models for assessing the ecosystem services such as ARIES (ARtificial Intelligence for Ecosystem Services), InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), and RIOS (Resource Investment Optimization System) (Dennedy-Frank et al. 2016; Lüke and Hack 2018). In this study, we have chosen a spatially explicit InVEST model. Spatially explicit models combine a spatial landscape map that describes the spatial distribution of features (Canqiang et al. 2012; Dunning et al. 1995). The InVEST model is a special tool for ecosystem services that is extensively utilized around the world and requires less data (Butsic et al. 2017; Cong et al. 2020). This model is gaining interest in the ecosystem services community (Hamel and Guswa 2015). The InVEST can be used directly for modeling different ecosystem services as opposed to traditional hydrological models such as SWAT (Benra et al. 2021; Lüke and Hack 2018). InVEST water yield model does not require a high level of expertise or extensive data analysis. The model runs on a gridded map at an annual average time step and it is a popular model of assessing ecosystem services (Wu et al. 2021; Yang et al. 2019). It is also able to simulate watershed responses satisfactorily (Goyal and Khan 2017). InVEST can provide scenario evaluations which are essential for policy-making and decision-making (Babbar et al. 2021; Redhead et al. 2016). The model quantifies the change in services from baseline conditions and various scenarios of land use and management. It is used to map and value the goods and services from the natural world that sustain and fulfill human life. It has different types of models such as crop production, sediment retention, and water yield, etc (Kadaverugu et al. 2021; Redhead et al. 2016). Terrado et al. (2014) used the InVEST model for assessing the impact of climate extremes on hydrological ecosystem services such as water provisioning, water purification, and erosion control in a Mediterranean basin. Marquès et al. (2013) applied this model to the Francoli river basin, Spain for finding the climate

change impact on water-related services and concluded that the basin will highly experience desertification. Hamel and Guswa (2015) analyzed the uncertainty of the water yield model in Cape Fear catchment, North Carolina, and found that the Z parameter is more sensitive as compared to K_c .

The objectives of this study are (1) to evaluate the sensitivity and applicability of InVEST model for water yield for the 1971-2000 period in the Tungabhadra river basin, India (2) to predict the water yield for future periods in a changing climate (2021-2040) and (3) to calculate the change in the hydropower production and its net present value (NPV) at Muniarabad and Bhadra dams. This work quantifies the change in the benefits of ecosystem services within future scenarios of climate change. The study is spatially explicit i.e. water yield, hydropower production, and valuation changes are calculated spatially over a period of time.

2. MATERIALS AND METHODS

2.1 Methodology

The flowchart illustrating the methodology of the study is shown in Figure 1. The first step in this study is the preparation of datasets such as precipitation, reference evapotranspiration, root restricting layer depth, plant available water content (PAWC), land use/land cover (LULC) with biophysical table and watershed maps. This data is then integrated into the InVEST model to get the water yield in volumetric units. Sensitivity analysis and parameter calibration exercises are performed to select optimum values of the parameters such as Zhang coefficient (Z) and evapotranspiration coefficient (K_c) so as to improve the simulation of yield when valiating with the observed streamflow. The consumptive use such as municipal and industrial water use is subtracted from the water yield, which results in the water that is entering the dam, called realized water. The yield for future scenarios is estimated using the NorESM climate data, which is used after bias correction. The hydropower production and its NPV at each dam are calculated using the realized water . Similarly, all steps are performed for future scenarios to calculate changes in the yield and hydropower production. Finally, the yield and hydropower production are calculated as percentage change.

2.2 Study area

The Tungabhadra River originates in Karnataka and enters the Krishna River in Bavapuram in Telangana. The location map of the study area is shown in Figure 2. It lies between latitudes $13^{\circ}8'06''$ and $16^{\circ}13'35''$ N and longitudes $74^{\circ}46'52''$ and $78^{\circ}01'29''$ E. It covers an area of 65,284 km² and the mean elevation of the basin is 978.5m. It has 3 major dams, namely Tungabhadra dam at Munirabad, Bhadra dam at Bhadravathi, and Vani Vilasa dam at Hiriyur. Among the three, Tungabhadra dam and Bhadra dam are used for hydropower production with a capacity of 39.20 MWH and 28 MWH, respectively. The Tungabhadra River is one of the main rivers that flows from southwest to northeast. The river basin has an annual mean precipitation of 1100 mm and the northwest part of the basin receives higher monsoon rainfall (Bisht et al. 2017). The average annual runoff in the basin is 200 thousand million cubic feet (TMC) and the net availability of groundwater is 189 TMC. Major crops grown in the basin are maize, paddy, pulses, and cotton.

The basin's net sown area is roughly 38,800 sq km, with only 11,626 sq km irrigated, accounting for 30% of the total sown area. This basin is chosen as the study location because of its enormous importance in Karnataka, which accounts for 37% of the state's total food production. Contaminated and depleted groundwater, sedimentation in reservoirs, head reach, and tail-ender problems all exist in the basin.

2.3 Data Requirement and Preparation

The InVEST model requires average annual precipitation, average annual reference evapotranspiration, LULC with biophysical table, root restricting layer depth, plant available water content, watershed, and sub-watershed maps, and data related to consumptive use and hydropower plant to calculate water yield and hydropower production. Because the model inputs should be in a projected coordinate system, the datasets are projected to WGS84 UTM Zone 43N, and the data is resampled to 100m spatial resolution using the nearest neighbor approach. Table 1 lists the data sources, resolution, software, and model used to create the datasets.

2.3.1 Meteorological Data

To calibrate the model, data from at least 10 years must be used to represent climatic change (Hamel and Guswa 2015). For the calibration and validation period, average yearly precipitation is

estimated using grid points from the Indian Meteorological Department (IMD) with a spatial resolution of 0.25 degrees (Pai et al. 2014) (https://www.imdpune.gov.in/Clim_Pred_LRF_New/GriddedData_Download.html). From rainfall data, 90% of rainfall is observed between June and October. Using the Thiessen polygon interpolation method, a raster dataset of average yearly precipitation was generated. Rainfall in the basin is varying spatially in the range of 378.91 mm to 3889.42 mm. The southwest monsoon passes across the western ghats, resulting in the maximum rainfall in the basin. The central part of the basin, which lies in the rain shadow, receives the least rainfall. The average annual rainfall variation in the basin is shown in Figure 3(a). The graph in Figure 4(a) shows the rainfall variation over the calibration period. The graph shows that the year 1975 had the most precipitation and 1976 had the least.

Maximum and minimum temperature data with 1 degree spatial resolution, acquired from IMD grid points, are used to calculate average yearly evapotranspiration (Bhaskar Rao et al. 2009). Figures 4(c) and 4(d) demonstrate the variance in maximum and minimum temperature across the calibration period. The average maximum temperature is 31.19 °C, which occurred in 1997, while the average minimum temperature is 19.50 °C, which occurred in 1976. The Hargreaves method is used for calculating ET_0 which is given below (Hargreaves and Samani 1985):

$$ET_0 = 0.0023 \times Ra \times \left[\frac{(T_{max} + T_{min})}{2} + 17.8 \right] \times (T_{max} - T_{min})^{0.5} \quad (1)$$

where T_{max} and T_{min} are maximum and minimum temperature in °C and R_a is terrestrial radiation defined as:

$$Ra = \frac{24 \times 60}{\pi} \times G_{SC} d_r [\omega_s \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \sin(\omega_s)] \quad (2)$$

where G_{SC} is the Solar constant (0.0820 MJ m⁻² min⁻¹), d_r is inverse of earth-sun distance, ω_s is the hour angle of sunset, ϕ is latitude, and δ is solar declination. The gridded map of ET_0 is prepared using the IDW interpolation method. Figure 3(b) depicts the regional variance of ET_0 , which ranges between 1588 and 1850 mm. The variation in ET_0 over the calibration period is shown in Figure 4(b) which shows that ET_0 is maximum in the year 1992 and minimum in 1978. Because of the

higher elevation in the southwest, evapotranspiration is lower (as elevation increases solar radiation and vapor pressure decreases).

2.3.2 Soil Data

Root restricting layer depth is shown in Figure 3(c) which is the soil depth at which the root growth becomes difficult. This layer is generated using the global data of the root restricting layer data prepared by Yang et al. (2006). The root restricting layer depth varying from 132 mm to 1788 mm in the basin. Plant available water content (PAWC) is the maximum amount of water that a plant can use for its growth, which can be calculated as the difference between field capacity and permanent wilting point of soil. It is prepared using Food and Agriculture Organization (FAO) soils data (Freddy et al. 2009) (<https://data.apps.fao.org/map/catalog/srv/eng/catalog.search?id=14116#/home>) and the Soil-Plant-Atmosphere-Water (SPAW) tool, which calculates PAWC in fractions of soil depth (Saxton and Rawls 2006) (<https://www.ars.usda.gov/research/software/download/?softwareid=492&modecode=80-42-0510>). PAWC values are varying from 0 to 0.149 as shown in Figure 3(d). SPAW calculates the available water in inch/ft based on the soil texture data (percentage of clay, sand, silt, and organic content fraction) and .

2.3.3 Watershed and Streamflow data

The watershed and sub-watershed maps were created using a CARTOSAT Digital Elevation Model (DEM) with a spatial resolution of 30 meters (<https://bhuvanapp3.nrsc.gov.in/data/download/index.php>). The basin's elevation ranges from 199 meters to 1758 meters, with the southernmost section having the highest elevation. The watershed boundary of the basin with streams is shown in Figure 3(e).

The Central Water Commission (CWC) provides streamflow data, and a gauge station is located at the outlet point of the watershed at Bawapuram, Telangana. Figure 4(e) depicts the variance in streamflow over the calibration period in Thousand Million Cubic Feet (TMC) units. The annual mean streamflow in the basin is 194 TMC. The graph shows that the maximum streamflow is 529 TMC which occurred in the year 1975 and the minimum is 35 TMC in 1976. As seen in Figure

4(a), a significant decline in streamflow in consecutive years is related to a severe reduction in rainfall. Figure 4(c) also shows that the maximum temperature increased from 1975 to 1976, which is one of the reasons for the decrease in streamflow; also, the streamflow is lower when ET_0 is higher.

2.3.4 Land Use / Land Cover (LULC) and Biophysical table

The LULC maps presented in Figure (f) are decadal LULC maps produced from NASA Earth data by Roy et al. (2016). The data is classified based on the IGBP Classification schema, which consists of 12 classes with a spatial resolution of 100m (https://daac.ornl.gov/VEGETATION/guides/Decadal_LULC_India.html). Agriculture occupies the majority of the land (70 percent), with major crops such as rice and maize. Forests, built-up land, and water bodies, etc. are examples of other land uses. The biophysical table is a Comma separated file that contains the information about the LULC map. The column names of the file contain lucode, LULC_desc, LULC_veg, root depth, and K_c . The lucode value of a class should resemble the pixel value in the raster data. LULC_veg gives the information about which equation to be used (equation 4 for vegetated land cover and 7 for others)

2.3.5 Zhang Coefficient

The Z parameter or Zhang coefficient is a constant value ranging from 1 to 30. It is a climate seasonality factor that captures the local precipitation pattern and hydrogeological characteristics of the catchment (Yang et al. 2019). There are three methods proposed to calculate the Z parameter in the InVEST model. The first method for estimating the Z parameter is based on globally available ω values. The second method uses the Z parameter, which is positively correlated with the number of rainfall events per year, N, and is calculated as $N/5$, where N is the number of rain events per year. In the third approach, Z was calibrated using the observed streamflow data. In our study, the average number of rainy days per year in the Tungabhadra basin was approximately 66, giving a Z value of 13.

2.3.6 Water Demand Table and Hydropower Valuation Table

The water demand table includes LULC classes as well as consumptive use for each land-use type. Industrial and municipal water use are included in the consumptive use. The environmental flow

requirement (EFR) is also used in this study to account for the ecosystem's role. EFR is the amount of water required to sustain freshwater ecosystems in a river basin. According to Smakhtin et al. (2006), 10% of total flow is used for EFR consumption in this study. Municipal water use is calculated based on population density and water use per person. The demand is expressed as cubic meters per year per pixel.

The hydropower valuation table includes information about hydropower stations in the basin, such as turbine efficiency, kilowatt-hour price of power (KWH), the height of water behind the powerhouse, the fraction of water used for hydropower production, the expected life span of the hydropower station, and the discount value of the currency over time.

2.3.7 Climate Model Data

The climate model data used in this study is from the Norwegian Earth System Model (NorESM) (Bentsen et al. 2013) (<https://esgf-node.llnl.gov/projects/cmip5/>). NorESM is based on the Community Climate System Model (CCSM) and Community Earth System Model (CESM) projects. Representative Concentration Pathways (RCP) with radiative forcings of 4.5 and 8.5 W/m² (RCP4.5 and RCP8.5) scenarios are used for this study. Because this data does not take into account leap days, the average of the 1st of March and the 28th of February is used to calculate the values of leap days, i.e. the 29th of February. The data is in NetCDF format, and it was extracted using Python programming. This data provides mean daily rainfall and temperature for the base scenario for the period between 1971 and 2000 and the future scenario between 2021 and 2040. Data is used after it is bias-corrected (quantile mapping) with IMD observed data. When comparing regional climate model simulations to observational data, quantile mapping is commonly used to correct biases (Maraun 2013).

3. InVEST Water Yield Model

The water yield model is divided into two sections: water yield, water scarcity, and valuation, and it is based on the Budyko curve (1974) (Hamel and Guswa 2015) (<https://naturalcapitalproject.stanford.edu/software/invest>). The following are the basic model equations from the InVEST Model manual:

3.1 Water yield

Water yield is calculated in the InVEST model as the sum and average of the water yields based on the principle of water balance at the sub-watershed level, and it is defined as the amount of water that runoff from the landscape (Yang et al. 2019).

Annual water yield $Y(x)$ for a pixel is calculated as:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x) \quad (3)$$

where $AET(x)$ is average annual actual evapotranspiration and $P(x)$ is the average annual precipitation of pixel x . For croplands and forest land use, $\frac{AET(x)}{P(x)}$ is calculated as

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^\omega\right]^{\frac{1}{\omega}} \quad (4)$$

where $PET(x)$ is annual potential evapotranspiration and $\omega(x)$ is a parameter characterizing climate- soil properties. The expressions for $PET(x)$ and $\omega(x)$ are as follows:

$$PET(x) = K_c(l_x) \times ET_0(x) \quad (5)$$

$$\omega(x) = Z \frac{AWC(x)}{P(x)} + 1.25 \quad (6)$$

where $AWC(x)$ is plant available water content and Z is a Zhang coefficient, which depends on the number of rain events per year, ET_0 is reference evapotranspiration and $K_c(l_x)$ is the evaporation factor for each LULC. For other land use types such as water bodies, build-up lands $AET(x)$ is calculated directly from reference evapotranspiration (ET_0) as

$$AET(x) = (K_c(l_x) \times ET_0(x), P(x)) \quad (7)$$

3.2 Hydropower Production and Valuation

Water used for other consumptive uses, such as drinking water and industrial use, is removed from the calculation of hydropower production, leaving only the actual water entering the dam termed as realized water, from which hydropower production and valuation are performed.

$$V_{in} = Y - u_d \quad (8)$$

where V_{in} is the realized supply (inflow to the reservoir), u_d is the consumptive use of water in the watershed upstream of dam d and Y is the total water yield from the watershed upstream of dam d .

Hydropower production is calculated for dam d in *KWH* as follows:

$$\varepsilon_d = 0.00272 \times \beta \times \gamma_d \times h_d \times V_{in} \quad (9)$$

where ε_d is hydropower generated in *KWH*, β is the turbine efficiency, γ_d is the percentage of inflow water volume to power stations, and h_d is the water level in dams. The NPV of the energy produced by the power station at dam, d is calculated as follows:

$$NPVH_d = (p_e \varepsilon_d - TC_d) \times \sum_{t=0}^{T-1} \frac{1}{(1+r)^t} \quad (10)$$

where TC_d is the operating costs for dam d , p_e indicates the market value of electricity for a *KWH*, T is the expected lifetime of the reservoir, and r is the discount rate.

4. RESULTS AND DISCUSSION

4.1 Water yield

Water yield is defined as the difference between precipitation and actual evapotranspiration for each land use pixel. Before projecting water yield for the future, the model is analyzed for its sensitivity to different parameters, and optimum parameters are selected by calibrating the model with observed data.

4.1.1 Sensitivity Analysis

The sensitivity of model parameters is calculated to determine which parameters are more sensitive to water yield. The parameters used for the analysis are the evapotranspiration coefficient (K_c) and zhang coefficient (Z). The sensitivity to water yield can be distinguished in terms of water yield calculated with baseline parameter values (standard values proposed in the literature). In this study, a sensitivity analysis method proposed by Morris (1991) is used. This method is known as a one-step-at-a-time method (OAT), which means that only one parameter is replaced while the other parameters remain constant.

Sensitivity to Z

The Z value sensitivity to water yield can be differentiated for water yield calculated with the baseline Z value. The baseline value is defined as the average number of rainfall days in a year divided by 5 (i.e., $Z=N/5$). The average number of rainfall days in the basin is 66, which, when combined with 30-year rainfall data, results in Z values of 13. The Z value ranges from 1 to 30, and

the range is defined by the extreme values of P and AWC across the various catchments (Canqiang et al. 2012). Figure 5(a) depicts the percent change in water yield (change in yield with respect to yield calculated using the baseline value) to Z, for example, when Z is 30, the percentage change is 40%, and when Z is 1, the change is 130%.

Sensitivity to K_c

Because cropland is the most common land cover in the catchment, the sensitivity of the evapotranspiration coefficient (K_c) is only tested for crop cover. Food and Agriculture Organization (FAO) proposed values of K_c for different land covers which were used in this study, it is seen that the baseline value is 1 for cropland, with a range of 0 to 1.5. The graph in Figure 5(b) shows the % change in water yield with the change in K_c . For example, if K_c is increased by 30%, the yield is reduced by 15%. This analysis shows that Z is more sensitive to modeled water yield than K_c .

4.1.2 Calibration and Validation

The model is calibrated for the base scenario (1971-2000) and validated for the period (2001-2010). Calibration is carried out on a yearly basis to determine how the simulated data correlates with the observed gauge data. Figure 6(a) and 6(b) depict scatterplots of observed versus simulated water yield for the calibration and validation periods, respectively. The analysis revealed that the model performed moderately to well, with a coefficient of determination (R^2) of 0.57 for the calibration period and 0.63 for the validation period. Calibration analysis yields optimum values of Z and K_c of 25 and 0.95, respectively. The overall simulated yield for the base scenario with optimum parameters is 279 TMC for the calibration period and 265 TMC for the validation period.

4.1.3 Water Yield Projection

NorESM climate data is used to predict water yield in the face of future climate change scenarios. Table 2 depicts the change in rainfall, AET, and water yield predicted by the InVEST model for future scenarios. Precipitation is expected to decrease between 1.31 % and 14.57 % for RCP 4.5 and 8.5 scenarios, while actual evapotranspiration (AET) is expected to increase by 7.40 % for RCP 4.5 and decrease by 5.72 % for RCP 8.5. This decrease in AET is due to the decrease in rainfall. The RCP 4.5 scenario reduces water yield by approximately 33% compared to the base scenario, while the RCP 8.5 scenario reduces water yield by 50%. The RCP 8.5 scenario predicts a significant

reduction in water yield. To compensate for the reduction in water yield, small reservoirs can be built, which can significantly improve retention and, ultimately, water yield. Changes in agricultural patterns and afforestation can also help to reduce the impact. Because this study does not account for changes in land use patterns that may affect water yield, the model may overestimate the result. Figure 7 depicts the range and spatial variation of water yield for the baseline and future scenarios. Due to high precipitation and low ET_0 , the southwest part of the basin (i.e. western ghats) contributes approximately 8% of total yield. The yield is very low in the central part of the basin, while it is higher in the northeast. The simulations show that the eastern part of the basin, which includes towns like Rayadurgam, Kalyandurg, and Amarapuram in Andhra Pradesh, is less vulnerable to climate change.

4.2 Hydropower Production and Valuation

For future scenarios, there is a reduction in hydropower production at reservoirs, similar to the reduction in water yield. Hydropower production is calculated at two hydropower stations near the reservoirs, Munirabad and Bhadra. Figure 2 depicts the locations of the power stations. The power produced at the station is calculated after computing the amount of water that reaches the dam, which is realized water (water yield minus consumptive use). The energy produced is valued using the net present value (NPV) as an indicator to assess the economic impact of climate change. NPV is defined as the present value of the cash flows at a required discount rate of the project (Gallo 2014). The NPV of hydropower production is calculated assuming that land use does not change over the dam's 100-year lifespan. For valuation, a monetary estimate is provided for the reservoir's entire remaining lifetime. Table 3 shows the hydropower production over its lifespan, as well as the value of the energy produced in rupees (in crores). The model considers the lifespan of the dam and assumes that the same amount of water that was available between 1971 and 2000 will eventually be available for more than 100 years. This results in an estimated power production of 131.19 Gigawatts (GW) valued at 1919.32 crores. However, it is expected to decrease in the future due to changes in precipitation and temperature. Future projection results show that the Bhadra power station is highly vulnerable, with reductions in energy production ranging from 59 % (RCP 4.5) to 67 % (RCP 8.5), while the Munirabad power station could see reductions ranging from 41

% (RCP 4.5) to 56 % (RCP 8.5). The bar graph in Figure 8(a) shows the difference in hydropower production and Figure 8(b) shows the difference in its NPV for the base and future scenarios for both power stations. With the decrease in the production of hydropower and the respective projected population growth, alternative energy sources would be looked for. Decision-makers should take the action required in this regard to reduce the risk related to the reduction of production of hydropower.

5. CONCLUSIONS

In this study, an assessment of water yield, hydropower production, and its valuation is carried out in the Tungabhadra river basin, India. In future, precipitation, evapotranspiration, water yield and hydropower production will decrease. In this research work, the InVEST model is used for the evaluation of water related ecosystem services. It is expected that the water yield from the models simulations will decrease from 33 to 50%. The production of hydropower takes place at Munirabad Power House and Bhadra Powerhouse, two important hydropower plants in the basin. The results show that the Munirabad dam will produce power and NPV from 41% to 56%, while Bhadra dams are expected to produce from 59% to 67%. A high reduction in water yield and power production is observed using data from the RCP 8.5 scenario. The analysis shows that production of hydropower is threatened by climate change. Decision-makers can use the results of this study to mitigate the impact of climate change in the region. This study's research methodology can be applied to other basins in the region. This work is important for the analysis of the energy-food nexus problems in the basins. Further research on hydrological simulations can enhance the results of this study.

DATA AVAILABILITY STATEMENT

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

- InVEST Model - <https://naturalcapitalproject.stanford.edu/software/invest>
- SPAW Software - <https://hrsl.ba.ars.usda.gov/SPAW/Index.htm>
- Climate Data - <http://www.imdpune.gov.in/ClimPredLRFNew/GriddedDataDownload.html>

- Soil data - <http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116>
- LULC Map - <http://dx.doi.org/10.3334/ORNLDAAAC/1336>
- Root restricting layer Depth - doi:10.1002/2016WR019392.
- DEM: <https://bhuvan-app3.nrsc.gov.in/data/download/index.php>
- Hydropower Data - <http://karnatakapower.com/en/technical/>

ACKNOWLEDGEMENTS

We would also like to convey appreciation to the anonymous reviewer and editor, whose comments have substantially improved this article. The corresponding author would like to thank for the partial support from the Virginia Agricultural Experiment Station (Blacksburg) and through the Hatch Program of the National Institute of Food and Agriculture at the United States Department of Agriculture (Washington, D.C.).

REFERENCES

- ACIWRM, and WRD. (2012). "River Basin Profile Tungabhadra Sub-Basin Karnataka." *Advanced Centre for Integrated Water Resources Management (ACIWRM) Water Resources Department (WRD)*, 1–20.
- Adhikari, K., and Hartemink, A. E. (2016). "Linking soils to ecosystem services - A global review." *Geoderma*, Elsevier B.V., 262, 101–111.
- Al-Hasan, A. A. S., and Mattar, Y. E. S. (2014). "Mean runoff coefficient estimation for ungauged streams in the Kingdom of Saudi Arabia." *Arabian Journal of Geosciences*, 7(5), 2019–2029.
- Allan, T., Keulertz, M., and Woertz, E. (2015). "The water–food–energy nexus: an introduction to nexus concepts and some conceptual and operational problems." *International Journal of Water Resources Development*, 31(3), 301–311.
- Babbar, D., Areendran, G., Sahana, M., Sarma, K., Raj, K., and Sivadas, A. (2021). "Assessment and prediction of carbon sequestration using Markov chain and InVEST model in Sariska Tiger Reserve, India." *Journal of Cleaner Production*, Elsevier Ltd, 278(123333), 1–17.
- Bangash, R. F., Passuello, A., Sanchez-Canales, M., Terrado, M., López, A., Elorza, F. J., Ziv, G., Acuña, V., and Schuhmacher, M. (2013). "Ecosystem services in Mediterranean river basin: Climate change impact on water provisioning and erosion control." *Science of the Total Environment*, Elsevier B.V., 458–460, 246–255.
- Bennett, E. M., Baird, J., Baulch, H., Chaplin-Kramer, R., Fraser, E., Loring, P., Morrison, P., Parrott, L., Sherren, K., Winkler, K. J., Cimon-Morin, J., Fortin, M. J., Kurylyk, B. L., Lundholm, J., Poulin, M., Rieb, J. T., Gonzalez, A., Hickey, G. M., Humphries, M., Bahadur KC, K., and Lapen, D. (2021). "Ecosystem services and the resilience of agricultural landscapes." *Advances in Ecological Research*, 64, 1–43.
- Benra, F., De Frutos, A., Gaglio, M., Álvarez-Garretón, C., Felipe-Lucia, M., and Bonn, A. (2021). "Mapping water ecosystem services: Evaluating InVEST model predictions in data scarce regions." *Environmental Modelling and Software*, 138(February).
- Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C., and Kristjánsson, J. E. (2013). "The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate."

Geoscientific Model Development, 6(3), 687–720.

- Bhaskar Rao, Srinivas, D., and Ratna, S. B. (2009). “Development of a high resolution daily gridded temperature data set (1969 – 2005) for the Indian region.” *Atmospheric Science Letters*, 10(October), 249–254.
- Bisht, D. S., Chatterjee, C., and Raghuwanshi, N. S. (2017). “Spatio-temporal trends of rainfall across Indian river basins.” *Theor Appl Climatol*, Theoretical and Applied Climatology.
- Butsic, V., Shapero, M., Moanga, D., and Larson, S. (2017). “Using InVEST to assess ecosystem services on conserved properties in Sonoma County, CA.” *California Agriculture*, 71(2), 81–89.
- Canqiang, Z., Wenhua, L., Biao, Z., and Moucheng, L. (2012). “Water Yield of Xitiaoxi River Basin Based on InVEST Modeling.” *Journal of Resources and Ecology*, 3(1), 50–54.
- Chaturvedi, R. K., Joshi, J., Jayaraman, M., Bala, G., and Ravindranath, N. H. (2012). “Multi-model climate change projections for India under representative concentration pathways.” *Current Science*, 103(7), 791–802.
- Cong, W., Sun, X., Guo, H., and Shan, R. (2020). “Comparison of the SWAT and InVEST models to determine hydrological ecosystem service spatial patterns, priorities and trade-offs in a complex basin.” *Ecological Indicators*, Elsevier, 112(June 2019), 106089.
- Dennedy-Frank, P. J., Muenich, R. L., Chaubey, I., and Ziv, G. (2016). “Comparing two tools for ecosystem service assessments regarding water resources decisions.” *Journal of Environmental Management*, Elsevier Ltd, 177, 331–340.
- Dibike, Y. B., and Coulibaly, P. (2005). “Hydrologic impact of climate change in the Saguenay watershed: Comparison of downscaling methods and hydrologic models.” *Journal of Hydrology*, 307(1–4), 145–163.
- Duku, C., Rathjens, H., Zwart, S. J., and Hein, L. (2015). “Towards ecosystem accounting: A comprehensive approach to modelling multiple hydrological ecosystem services.” *Hydrology and Earth System Sciences*, 19(10), 4377–4396.
- Dunning, J. B., Stewart, D. J., Danielson, B. J., Noon, B. R., Root, T. L., and Stevens, E. E. (1995). “SPATIALLY EXPLICIT POPULATION MODELS : CURRENT FORMS AND FUTURE USES 1.” 5(1), 3–11.
- Endo, A., Tsurita, I., Burnett, K., and Orenco, P. M. (2017). “A review of the current state of research

on the water, energy, and food nexus.” *Journal of Hydrology: Regional Studies*, Elsevier B.V., 11, 20–30.

Fisher, B., and Kerry Turner, R. (2008). “Ecosystem services: Classification for valuation.” *Biological Conservation*, 141(5), 1167–1169.

Fisher, B., Turner, R. K., and Morling, P. (2009). “Defining and classifying ecosystem services for decision making.” *Ecological Economics*, Elsevier B.V., 68(3), 643–653.

Francesconi, W., Srinivasan, R., Pérez-Miñana, E., Willcock, S. P., and Quintero, M. (2016). “Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review.” *Journal of Hydrology*, Elsevier B.V., 535, 625–636.

Freddy, N., Harrij van, V., and Luc, V. (2009). “Harmonized World Soil Database.” *19th World Congress of Soil Science, Soil Solutions for a Changing World*, 43.

Fu, B., Wang, Y. K., Xu, P., Yan, K., and Li, M. (2014). “Value of ecosystem hydropower service and its impact on the payment for ecosystem services.” *Science of the Total Environment*, 472, 338–346.

Gallo, A. (2014). “A Refresher on Net Present Value.” *Harvard Business Review*, 1–3.

Goasin, A. ., Rao, S., and Basuray, D. (2018). “Climate change impact assessment on hydrology of Indian river basins.” *Current Science*, 90(3), 346–353.

Goyal, M. K., and Khan, M. (2017). “Assessment of spatially explicit annual water-balance model for Sutlej River Basin in eastern Himalayas and Tungabhadra River Basin in peninsular India.” *Hydrology Research*, 48(2), 542–558.

Goyal, M. K., and Surampalli, R. Y. (2018). “Impact of Climate Change on Water Resources in India.” *Journal of Environmental Engineering (United States)*, 144(7).

Green, P. A., Vörösmarty, C. J., Harrison, I., Farrell, T., Sáenz, L., and Fekete, B. M. (2015). “Freshwater ecosystem services supporting humans : Pivoting from water crisis to water solutions.” *Global Environmental Change*, Elsevier Ltd, 34, 108–118.

Grizzetti, B., Lanzasova, D., Liqueste, C., Reynaud, A., and Cardoso, A. C. (2016). “Environmental Science & Policy Assessing water ecosystem services for water resource management.” *Environmental Science and Policy*, Elsevier Ltd, 61, 194–203.

- Hamel, P., and Guswa, A. J. (2015). "Uncertainty analysis of a spatially explicit annual water-balance model: Case study of the Cape Fear basin, North Carolina." *Hydrology and Earth System Sciences*, 19(2), 839–853.
- Hargreaves, G. H., and Samani, Z. A. (1985). "Reference Crop Evapotranspiration from Ambient Temperature." *Applied Engineering in Agriculture*, 1(2), 96–99.
- Harshavardhan, P. L., Nayak, P. C., and Kumar, S. (2020). "Spatio-temporal Rainfall Variability and Trend Analysis for Krishna River Basin in India Spatio-temporal Rainfall Variability and Trend Analysis for Krishna River Basin in India." (June).
- Jayanthi, S. L. S. V., and Keesara, V. R. (2019). "Climate change impact on water resources of medium irrigation tank." *ISH Journal of Hydraulic Engineering*, Taylor & Francis, 00(00), 1–12.
- Kadaverugu, A., Nageshwar Rao, C., and Viswanadh, G. K. (2021). "Quantification of flood mitigation services by urban green spaces using InVEST model: a case study of Hyderabad city, India." *Modeling Earth Systems and Environment*, Springer International Publishing, 7(1), 589–602.
- Kandlikar, M., and Sagar, A. (1999). "Climate change research and analysis in India : an integrated assessment of a South — North divide." *Global Environmental Change*, 9, 119–138.
- Kang, H., Sridhar, V. (2018). "Improved drought prediction using near real-time climate forecasts and simulated hydrologic conditions", *Sustainability*, 10, 1799, doi: 10.3390/su10061799
- Karabulut, A., Egoh, B. N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Bouraoui, F., Aloe, A., Reynaud, A., Maes, J., Vandecasteele, I., and Mubareka, S. (2016). "Mapping water provisioning services to support the ecosystem-water-food-energy nexus in the Danube river basin." *Ecosystem Services*, 17(2016), 278–292.
- Klein, A. M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., and Tscharrntke, T. (2007). "Importance of pollinators in changing landscapes for world crops." *Proceedings of the Royal Society B: Biological Sciences*, 274(1608), 303–313.
- Li, M., Singh, V. P., Fu, Q., Liu, D., Li, T., and Zhou, Y. (2021). "Optimization of agricultural water–food–energy nexus in a random environment: an integrated modelling approach." *Stochastic Environmental Research and Risk Assessment*, 35(1), 3–19.
- Lüke, A., and Hack, J. (2018). "Comparing the applicability of commonly used hydrological

- ecosystem services models for integrated decision-support.” *Sustainability (Switzerland)*, 10(2).
- Malik, R. P. S. (2002). “Water-Energy Nexus in Resource-poor Economies : The Indian Experience.” *International Journal of Water Resources Development*, 18(1), 47–58.
- Maraun, D. (2013). “Bias correction, quantile mapping, and downscaling: Revisiting the inflation issue.” *Journal of Climate*, 26(6), 2137–2143.
- Marquès, M., Bangash, R. F., Kumar, V., Sharp, R., and Schuhmacher, M. (2013). “The impact of climate change on water provision under a low flow regime: A case study of the ecosystems services in the Francoli river basin.” *Journal of Hazardous Materials*, Elsevier B.V.
- Morris, M. D. (1991). “Factorial sampling plans for preliminary computational experiments.” *Technometrics*, 33(2), 161–174.
- Naderi, M. M., Mirchi, A., Bavani, A. R. M., Goharian, E., and Madani, K. (2021). “System dynamics simulation of regional water supply and demand using a food-energy-water nexus approach: Application to Qazvin Plain, Iran.” *Journal of Environmental Management*, Elsevier Ltd, 280(December 2020), 111843.
- Nelson, E. J., and Daily, G. C. (2010). “Modelling ecosystem services in terrestrial systems.” *F1000 Biology Reports*, 2(1), 1–6.
- Pai, D. S., Sridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S., and Mukhopadhyay, B. (2014). “Development of a new high spatial resolution (0.25° x 0.25°) long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region.” *Mausam*, 65(January), 1–18.
- Redhead, J. W., Stratford, C., Sharps, K., Jones, L., Ziv, G., Clarke, D., Oliver, T. H., and Bullock, J. M. (2016a). “Science of the Total Environment Empirical validation of the InVEST water yield ecosystem service model at a national scale.” *Science of the Total Environment*, Elsevier B.V., 1–9.
- Redhead, J. W., Stratford, C., Sharps, K., Jones, L., Ziv, G., Clarke, D., Oliver, T. H., and Bullock, J. M. (2016b). “Empirical validation of the InVEST water yield ecosystem service model at a national scale.” *Science of the Total Environment*, Elsevier B.V., 569–570, 1418–1426.
- Sahle, M., Saito, O., Fürst, C., and Yeshitela, K. (2019). “Quantifying and mapping of water-related ecosystem services for enhancing the security of the food-water-energy nexus in tropical data–

- sparse catchment.” *Science of the Total Environment*, 646, 573–586.
- Saxton, K. E., and Rawls, W. J. (2006). “Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions.” *Soil Science Society of America Journal*, 70(5), 1569–1578.
- Sehgal, V., Sridhar, V. (2018) "Effect of hydroclimatological teleconnections on watershed-scale drought predictability in Southeastern U.S.", *International Journal of Climatology*, 38 S1, e1139–e1157, doi: 10.1002/joc.5439
- Seong, C., Sridhar, V., Billah, M.M. (2018) "Implications of potential evapotranspiration methods for streamflow estimation in a changing climate", *International Journal of Climatology*, 38, 2, 896–914 doi:10.1002/joc.5218
- Smajgl, A., Ward, J., and Pluschke, L. (2016). “The water-food-energy Nexus - Realising a new paradigm.” *Journal of Hydrology*, 533, 533–540.
- Sridhar, V., Wedin, D.A. (2009) "Hydrological behavior of Grasslands of the Sandhills: Water and Energy Balance Assessment from Measurements", *Treatments and Modeling, Ecohydrology*, 2, 195-212, doi:10.1002/eco.61
- Sridhar, V., M. M. Billah, J. Hildreth (2018) "Coupled Surface and Groundwater Hydrological Modeling in a Changing Climate", *Groundwater*, 56, 4, 618-635, doi:10.1111/gwat.12610
- Sridhar, V., Kang, H., Ali, S.A. (2019). "Human-induced alterations to land use and climate and their responses on hydrology and water management in the Mekong River basin", *Water*, 11, 1307, doi:10.3390/w11061307
- Sujatha, E.R., Sridhar, V. (2018) "Spatial Prediction of Erosion Risk of a small mountainous watershed using RUSLE: A case-study of the Palar sub-watershed in Kodaikanal, South India", *Water*, 10, 1608; doi:10.3390/w10111608
- Terrado, M., Acuna, V., Ennaanay, D., Tallis, H., and Sabater, S. (2014). “Impact of climate extremes on hydrological ecosystem services in a heavily humanized Mediterranean basin.” *Ecological Indicators*, 37, 199–209.
- Tirupathi, C., Hatikonda, S. H. T., and Eesara, V. E. R. E. K. (2020). “Assessment of water resources and crop yield under future climate scenarios : A case study in a Warangal district of Telangana , India.” *journal of earth system and sciences*, 0123456789, 1–17.
- Wagstaff, R. K., and Wortman, S. E. (1999). “Ecosystem services in urban areas.” *Ecological*

Economics, 29(1), 293–301.

Wallace, K. J. (2007). “Classification of ecosystem services: Problems and solutions.” *Biological Conservation*, 139(3–4), 235–246.

Wu, Y., Xu, Y., Yin, G., Zhang, X., Li, C., Wu, L., Wang, X., Hu, Q., and Hao, F. (2021). “A collaborated framework to improve hydrologic ecosystem services management with sparse data in a semi-arid basin.” *Hydrology Research*, 1–14.

Yang, D., Liu, W., Tang, L., Chen, L., Li, X., and Xu, X. (2019). “Landscape and Urban Planning Estimation of water provision service for monsoon catchments of South China : Applicability of the InVEST model.” *Landscape and Urban Planning*, Elsevier, 182(October 2018), 133–143.

Yang, Y., Donohue, R. J., and McVicar, T. R. (2006). “Global estimation of effective plant rooting depth: Implications for hydrological modeling.” *Water Resources Research RESEARCH*, 52, 8260–8276.

List of Figures

- 1 Flowchart illustrating the methodology for calculating water yield and hydropower generation.
- 2 Location map of Tungabhadra basin and the Hydropower stations.
- 3 Geospatial data of Tungabhadra basin (a) precipitation, (b) reference ET_0 , (c) root depth, (d) PAWC, (e) watershed and (f) Land use/Land cover (LULC).
- 4 The graphs show the change in (a) Precipitation (b) ET_0 (c) Maximum Temperature and (d) Minimum Temperature and (e) Observed stream flow per year over the calibration period (1971-2000).
- 5 Graphs showing the sensitivity of (a) Z to water yield and (b) K_c to water yield.
- 6 Scatter plots for (a) the calibration period (1971-2000) and (b) the validation period (2001-2010).
- 7 Water yield in TMC/Yr for (a) Base Scenario (1971- 2000), (b) Future scenario (2021-2040) RCP 4.5, and (c) Future scenario (2021- 2040) RCP8.5 in the Tungabhadra basin.
- 8 (a) Hydropower production, and (b) Net Present Value at Munirabad and Bhadra power house for the base scenario (1971-2000) and future scenarios (2021-2040).

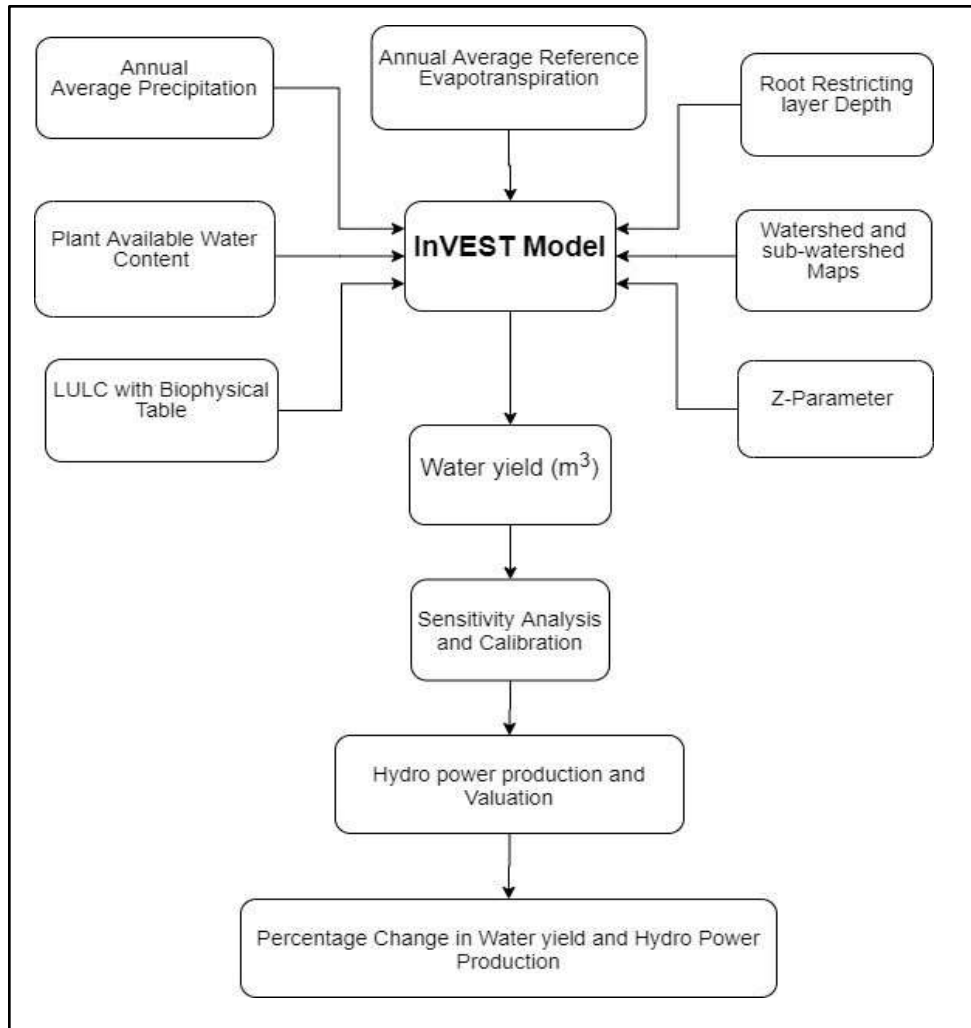


Figure 1: Flowchart illustrating the methodology for calculating water yield and hydropower generation

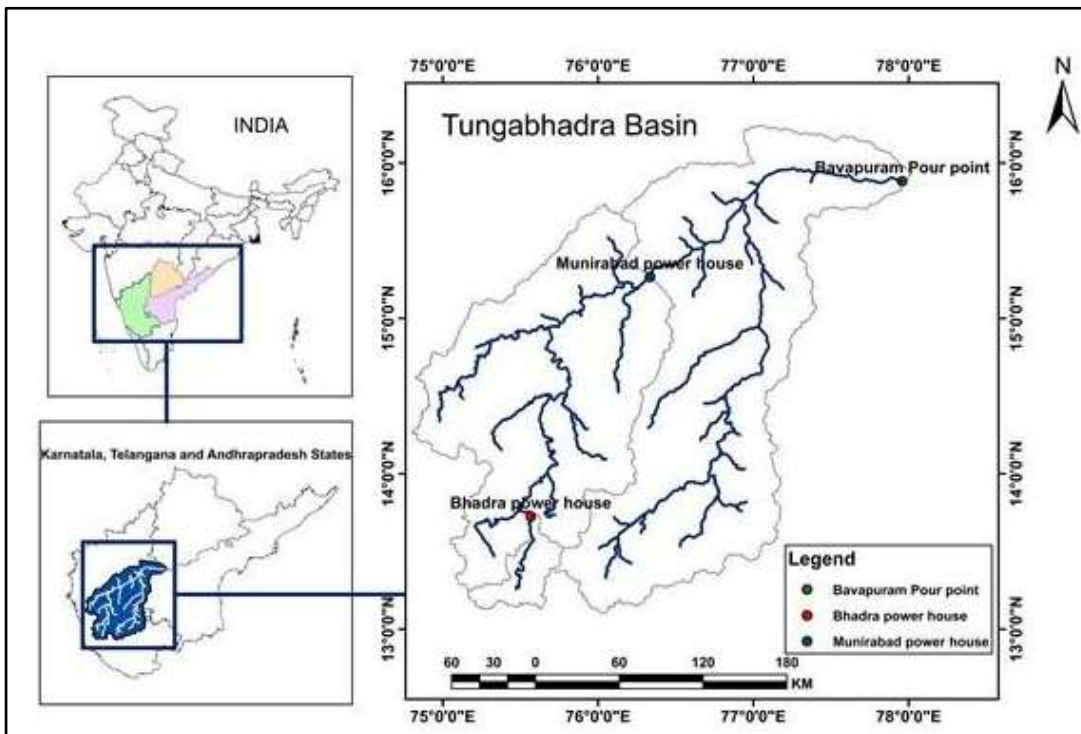


Figure 2: Location map of Tungabhadra basin and the Hydropower stations.

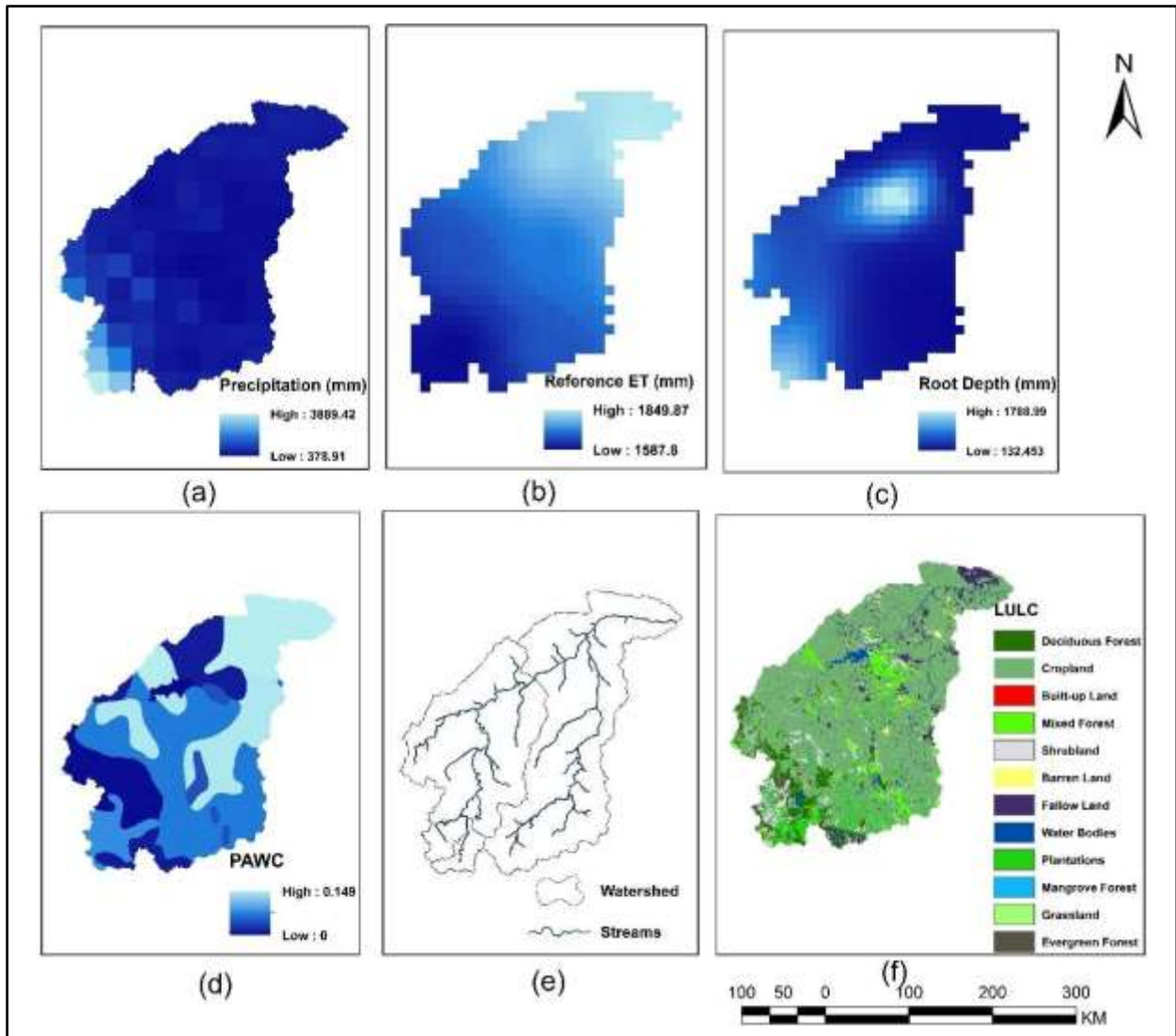
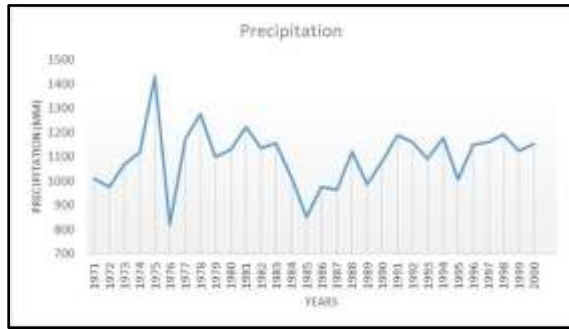
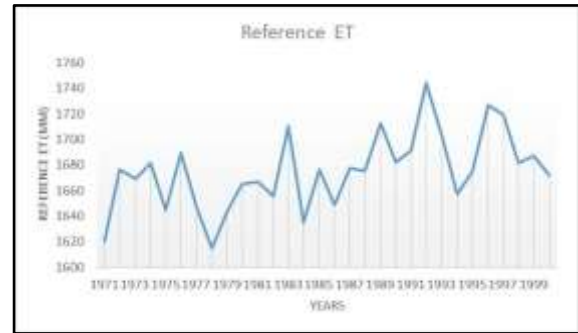


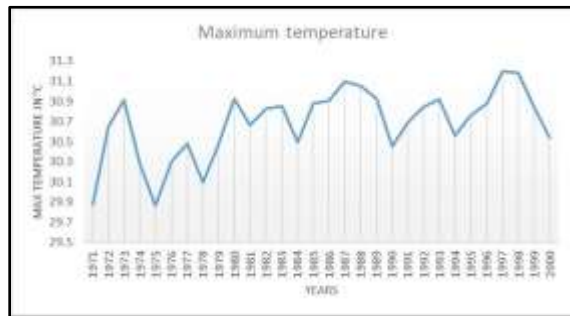
Figure 3: Geospatial data of Tungabhadra basin (a) Precipitation, (b) Reference ET_0 , (c) Root depth, (d) PAWC, (e) Watershed and (f) Land Use/ Land Cover (LULC)



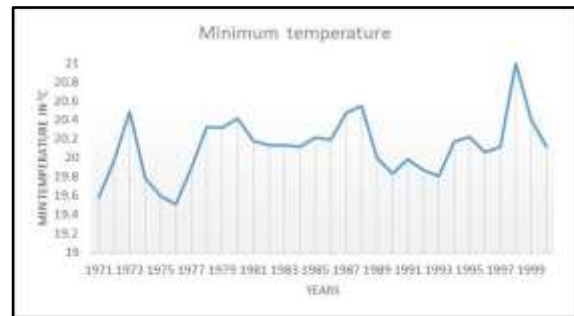
(a)



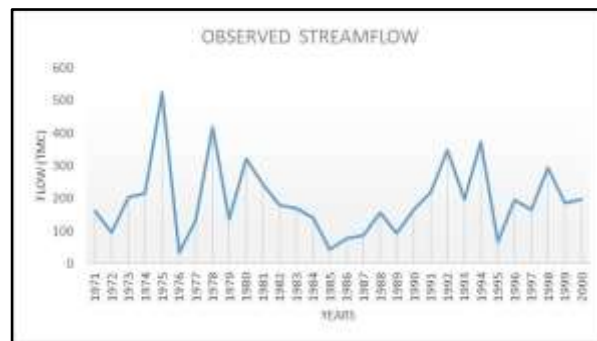
(b)



(c)

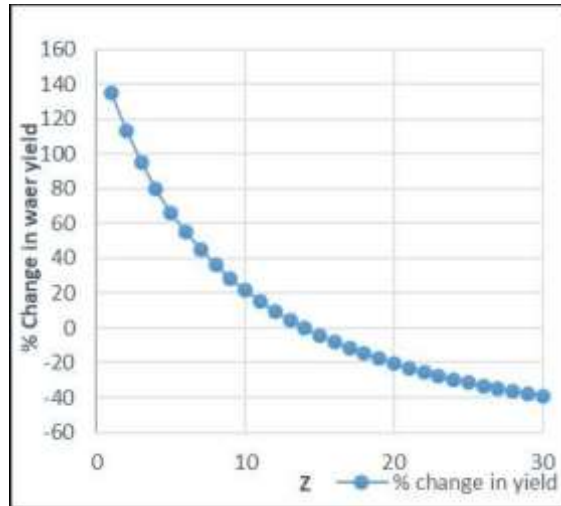


(d)

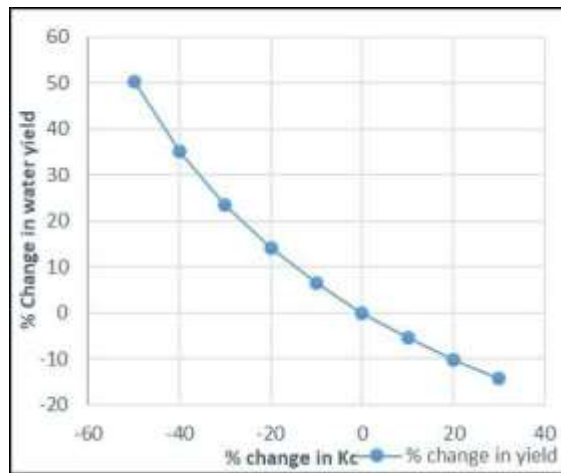


(e)

Figure 4: The graphs shows the variation in (a) Precipitation (b) ET_0 (c) Maximum Temperature and (d) Minimum Temperature and (e) Observed stream flow per year over the calibration period (1971-2000)

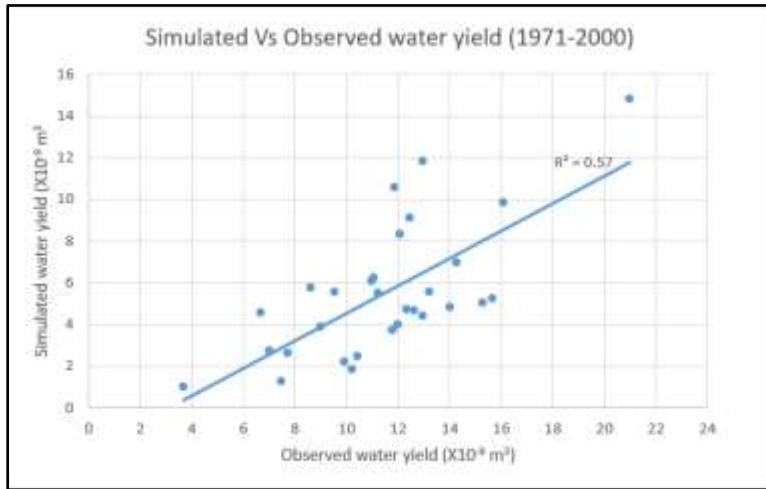


(a)

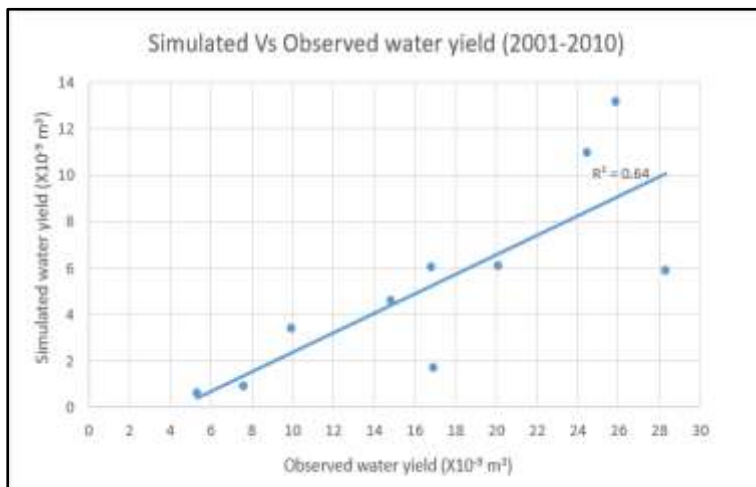


(b)

Figure 5: Graphs showing the sensitivity of (a) Z to water yield and (b) Kc to water yield.



(a)



(b)

Figure 6: Scatter plots for (a) Calibration period (1971-2000) and (b) Validation period (2001-2010).

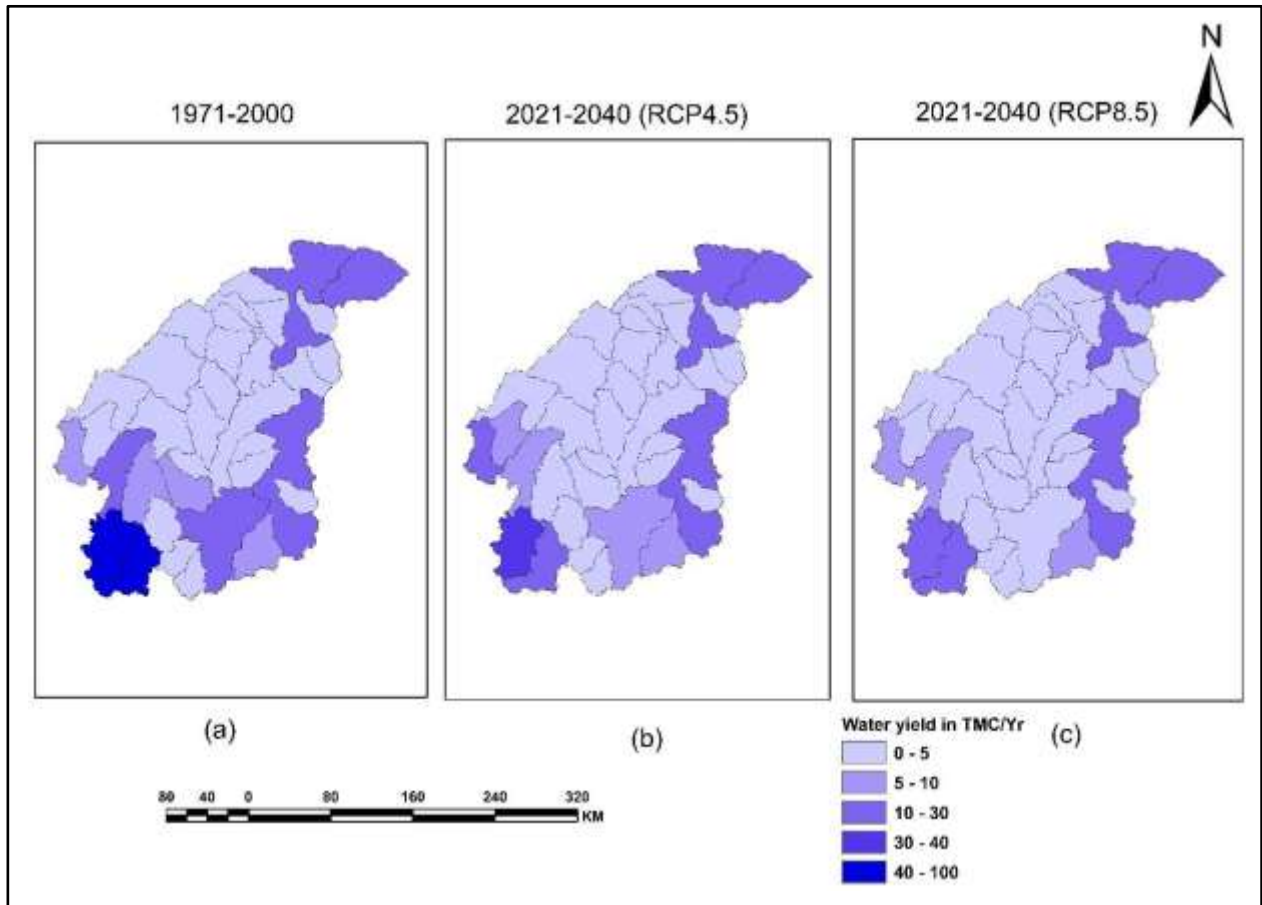
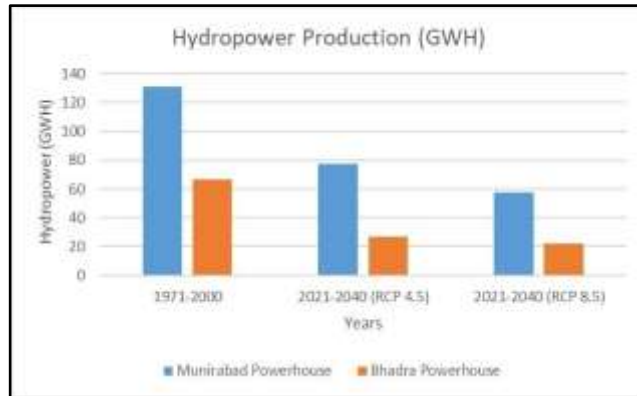
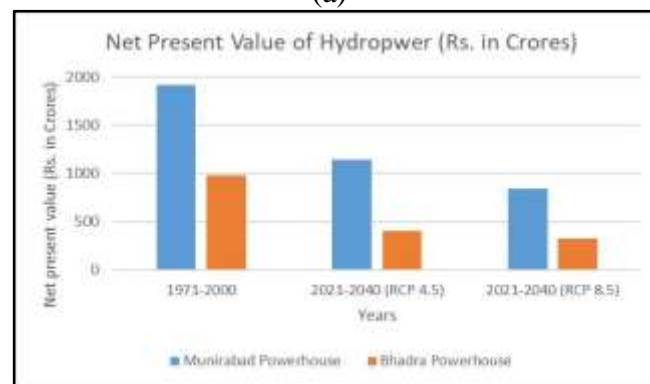


Figure 7: Water yield in TMC/Yr over the Tungabhadra basin for (a) Base Scenario (1971-2000), (b) Future scenario (2021-2040) RCP 4.5 and (c) Future scenario (2021-2040) RCP8.5.



(a)



(b)

Figure 8: (a) Hydropower production and (b) its Net Present Value at Munirabad and Bhadra power house for Base scenario (1971-2000) and future scenarios (2021-2040).

List of Tables

- 1 Datasets used in the InVEST model
- 2 Changes in rainfall, AET and water yield for future scenarios compared to the base scenario
- 3 Changes in hydropower production and net present value for future scenarios compared to base scenario for Munirabad and Bhadra power plants

Table 1: Datasets used in the InVEST model

Data	Year	Source	Tool/Equation	Resolution
Precipitation	1971-2010	IMD Precipitation	ArcMAP Software	0.25°X0.25°
	2021-2040	NorESM	ArcMAP Software	0.5°X0.5°
Reference ET	1971-2010	IMD Temperature	Hargreaves Equation	1°X1°
	2021-2040	NorESM	Hargreaves Equation	0.5°X0.5°
Root Depth map	-	Yang et al. (2016)	ArcMAP Software	0.5°X0.5°
Plant available water content	-	FAO soil data	SPAW Software	0.25°X0.25°
LULC	1985	Roy et al. (2016)	ArcMAP Software	100mX100m
Watershed	-	CartoDEM	ArcMAP Software	-

Table 2: Changes in rainfall, AET and water yield for future scenarios compared to the base scenario

Period	Scenario	Rainfall (mm/yr)		AET(mm/yr)		Yield (TMC/yr)	
		Production	% change	Production	% change	Production	% change
1971-2000	Base scenario	735.43	-	591.52	-	279.12	-
2021-2040	RCP 4.5	725.78	1.31%	635.29	-7.40%	186.06	33.34%
2021-2040	RCP 8.5	628.27	14.57%	557.72	5.72%	140.35	49.72%

Table 3: Changes in hydropower production and net present value for future scenarios compared to base scenario for Munirabad and Bhadra power plants

Period	Scenario	Munirabad Power House			Bhadra Power House		
		Hydropower Production (GW per 100 years)	Net Present value (Rs.) (in Crores)	% change	Hydropower Production (GW per 100 years)	Net Present value (Rs.) (in Crores)	% change
1971-2000	Base scenario	131.19	1919.32	-	66.90	978.85	-
2021-2040	RCP 4.5	77.74	1137.45	41%	27.17	397.50	59%
2021-2040	RCP 8.5	57.63	843.19	56%	22.25	325.56	67%