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Assessing the Impact of Climate Change on Surface Water Availability and Hydro Power Generation from an Existing Project

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Abstract : Generation of hydroelectric power by a project depends upon the properties of inflows and the effective head. Properties of a catchment may changes due to changes in landuse and land cover whereas the climate of the catchment may change due to local and global factors. Distributed catchment models are the best tools to estimate the inflows to a reservoir in the changed climatic conditions. The present study aimed to assess the impact of climate change on hydropower generation from an existing storage project. Using the data of the topography, landuse, meteorology, and measured catchment outflows, hydrological modeling was carried out using the SWAT (Soil Water Assessment Tool) model. After a satisfactory calibration and validation, the model setup was employed to determine the outflow from the catchment under the changed scenarios of climate. The precipitation and temperature series for the future conditions were constructed based on trend analysis and the projections for the region given by IPCC (2007). Catchment modeling under the changed scenario was carried out and firm power and energy generation from the project were re-assessed. The results were used to quantify the impact of climate change on hydropower generation from the project.

Keywords climate change, hydropower, SWAT model, surface water

INTRODUCTION

River basins are considered as the ideal natural units to address water resource development and management issues comprehensively. The impact of climate change on river basins will vary depending upon the location. Flood magnitude and frequency could increase in many regions as a consequence of increased frequency of heavy precipitation events, which will increase runoff in most areas. Stream flow during seasonal low flow periods would decrease in many areas due to more evaporation; changes in precipitation may offset the effects of increased evaporation.

Hydropower generation depends on availability of water and effective head. The climate change is likely to change in water availability and effective head that caused a change in will impact hydropower production. Some studies that have attempted to examine the impact of climate change on hydropower generation include Oud (2002), Lehner et al. (2005), Harrison et al. (2007), Kilsby et al. (2007), Schaefli et al. (2007) and Lucena et al. (2009)

The present study aims to assess the impact of climate change on hydropower generation from Wonogiri Hydropower project Indonesia. Using the data pertaining to topography, landuse, meteorology, and measured catchment outflows, hydrological modeling was carried out by using the SWAT (Soil Water Assessment Tool) model. After calibration and validation, the model setup was employed to determine the yield from the catchment under the changed scenarios of climate. A reservoir operation simulation model was used to compute hydropower generation.

STUDY AREA

The study area covers the catchment of the Wonogiri dam (area 1,260 km^2). The Wonogiri multipurpose dam is the only large dam on the mainstream of the Bengawan Solo River, which is the largest river in the Java (Indonesia) with a catchment area of around 16,100 km^2 and a length of about 600 km (Figure 1).

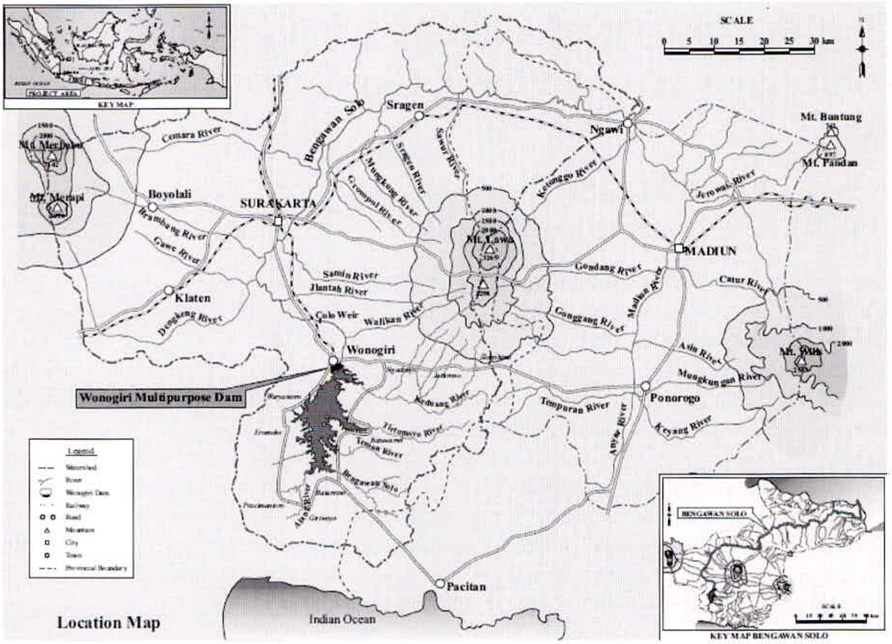

Fig. 1. The Study Area

The Bengawan Solo River rises on southwest slope of mountain Rahtawu in Tertiary Volcanic mountains area, and flows westward along the mountains. The Solo River runs northward receiving Alang River, Temon River, Tirutomoyo River and Keduang River immediately upstream of the Wonogiri Dam. The climate of the study area is tropical monsoon. The south-west to north-west winds prevail from November to April and they bring rains to the river basin, while the period from July to October is the dry season in which the basin is dried up by the south and south-east winds.

Hydro-meteorological data used for this study was collected from *Proyek Bengawan Solo* (PBS) and Irrigation Services, and also from previous project reports. Mean annual temperature at the Wonogiri dam is approximately 27.2 °C and it fluctuates from the minimum mean monthly temperature of 20.9 °C in July to the maximum mean monthly temperature of 33.3 °C in October. Temperature in the dry season (especially from June through August) is relatively low.

FUTURE CLIMATE SCENARIOS

In this study, trend of climate change was determined using the Mann–Kendall (MK) statistical test. This a non-parametric test to identify trends in a time series. The trend test is applied to a time series x_i, $i = 1, 2, ..., n$. The test compares the relative magnitudes of sample data. The MK statistic (S) is given by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign\left(x_j - x_k\right) \tag{1}$$

where :

$$sign\left(x_j - x_k\right) = \begin{cases} 1 & if\ x_j - x_k > 0 \\ 0 & if\ x_j - x_k = 0 \\ -1 & if\ x_j - x_k < 0 \end{cases} \tag{2}$$

A very high positive value of S indicates an *increasing* trend, and a very low negative value indicates a *decreasing* trend. However, it is necessary to compute the probability associated with S and the sample size (n) to statistically quantify the significance of the trend. The test statistic z_{mk} is estimated as

$$Z_{mk} = \frac{S-1}{[VAR(S)]^{1/2}} \quad if \;\; S > 0$$
$$= 0 \qquad if \;\; S = 0 \tag{3}$$
$$= \frac{S+1}{[VAR(S)]^{1/2}} \quad if \;\; S < 0$$

The variance of S, VAR(S) was computed by:

$$VARS(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p (t_p - 1)(2t_p + 5) \right] \tag{4}$$

where g is the number of tied groups (a tied group is a set of sample data having the same value), and t_p is the number of data points in the p^{th} group. The slope estimates of N pairs of data were computed using Sen's estimator of slope:

$$Q_i = \frac{x_j - x_k}{j-k} \tag{5}$$

where, x_j and x_k are data values at times j and k ($j > k$) respectively. The median of these N values of Q_i is Sen's estimator of slope. If N is odd, then Sen's estimator is computed by $Q_{med} = Q_{(N+1)/2}$ and if N is even, then Sen's estimator is computed by $Q_{med} = [Q_{N/2} + Q_{(N+2)/2}]/2$. The results of analysis using the MK test are shown in Table 1.

Recommendations from the IPCC (2007) for South-East Asia region were also used to obtain more comprehensive data about the trends of climate in the study area. Using all these values, climate change scenarios for this study were prepared as shown in Table 2.

For the long-term scenario, trend in temperature could not be analyzed because requisite data were not available and hence only IPCC (2007) recommendation were study used. This is the reason that there is no variation in the temperature change data for long-term scenarios.

WATERSHED MODELING USING SWAT MODEL

SWAT is a river basin scale model 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 (Neitsch, 2005). SWAT allows a number of physical processes to be simulated in the

Table 1. Result of Mann-Kendall Statistical Test

Scenario		Year	Parameter	DJF	MAM	JJA	SON
Temperature	Medium Term	1984-2003	Zmk	0.94	0.13	-1.30	0.55
			Q	-0.1	+0.4	-0.5	+0.7
Precipitation	Medium Term	1984-2003	Zmk	-0.78	0.93	-0.50	-0.19
			Q (mm)	-7.82	4.58	-0.63	-3.19
			Q (%)	-3	3	1	-3
	Long Term	1946-1995	Zmk	-0.55	-1.42	-0.39	-0.69
			Q (mm)	-31.69	-1.55	-1.93	-9.97
			Q (%)	-12	-1	-3	-9

Table 2. Climate Scenario used for simulation

Scenario	Year	Seasons	Change in	
			Precipitation (%)	Temperature (°C)
Medium-Term (Scenario II)	2024 - 2043	DJF	-3	-0.1
		MAM	0	0.4
		JJA	-1	-0.5
		SON	-3	0.7
Medium-Term (Scenario I)	2024 - 2043	DJF	2	2.25
		MAM	3	2.32
		JJA	0	2.13
		SON	-1	1.32
Long-Term (Scenario II)	2074 - 2093	DJF	-12	3.92
		MAM	-1	3.83
		JJA	-3	3.61
		SON	-9	3.72
Long-Term (Scenario I)	2074 - 2093	DJF	8	3.92
		MAM	12	3.83
		JJA	9	3.61
		SON	9	3.72

watershed. For modeling purposes, a watershed may be partitioned into a number of sub-watersheds or subbasins. The use of subbasins in a simulation is particularly beneficial when different areas of watershed are dominated by land uses or soil dissimilar enough to impact hydrology.

To model the catchment with the SWAT model, the Wonogiri watershed area was divided into 20 sub-watersheds as shown in Figure 2. After the input data was processed and the model was set-up, the next step is the process of calibration and validation of SWAT model. The available observed discharge data pertain to 1994-2003 period. For calibration, data for the years 1994 to 1999 were used, whereas the data for the years 2000-2003 were used for validation. SWAT model parameters were systematically adjusted to match the observed and computed behaviour.

Besides the graphical plots and tabular results, three statistical techniques, Nash-Sutcliffe coefficient (E), coefficient of determination (R^2), and relative error (RE) were used (White, 2005). SWAT model calibration was performed by minimizing the RE (in percent) at the gauged locations:

$$(RE\%) = \left|\frac{(O-P)}{O}\right| x100 \qquad (6)$$

where O is the measured value and P is the predicted output. The SWAT model was further calibrated using the Nash-Sutcliffe efficiency (E) which is defined as:

$$E = 1 - \sum_{i=1}^{n}(O_i - P_i)^2 \Big/ \sum_{i=1}^{n}(O_i - O_{avg})^2 \qquad (7)$$

where O_i are the measured values, P_i are the predicted outputs, O_{avg} is the average of measured value and i equals the number of values. Coefficient of determination (COD) denoted by R^2 was also calculated. The R^2 statistic is calculated as:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - O_{avg})(P_i - P_{avg})}{\left[\sum_{i=1}^{n}(O_i - O_{avg})^2 \sum_{i=1}^{n}(P_i - P_{avg})^2\right]^{0.5}}\right)^2 \qquad (8)$$

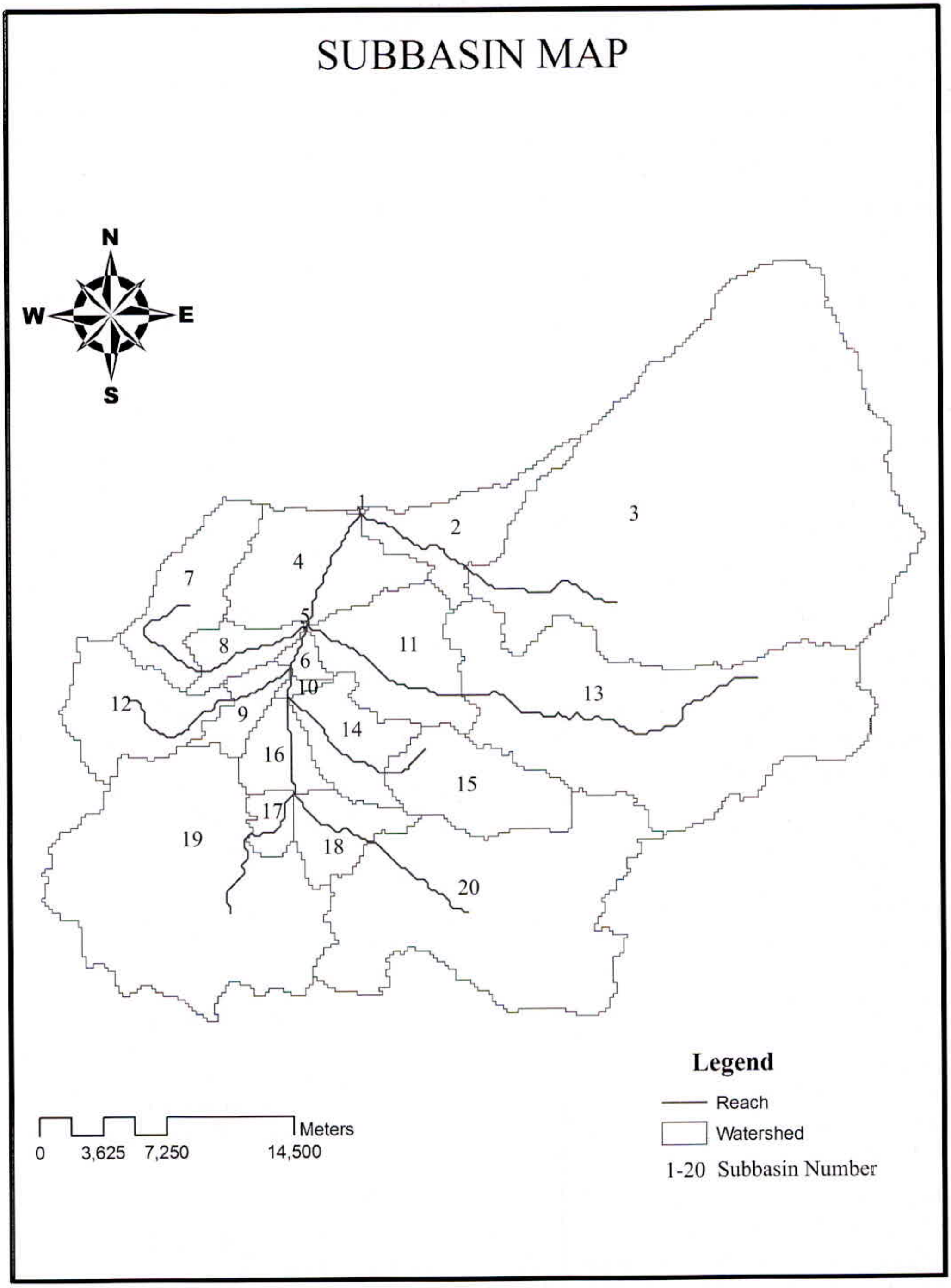

Fig. 2. Map showing sub-basins of the study area

The aim of a model calibration is to minimize RE and to maximize E and COD. The SWAT model quite accurately computed the flows including the zero flows in the validation period. For the calibration period (1994-1999), RE, E, and COD were -7.121, 0.924, and 0.87; these indices for the validation period (2000-2003) were 6.54, 0.939, and 0.892 respectively. Figure 3 shows the final result of the calibration process. These results are considered acceptable.

CLIMATE CHANGE SCENARIOS

Using the calibrated SWAT model parameters, the stream flow was calculated by the SWAT model with changed precipitation and temperature data for the different climate scenarios (Table 2). The statistical description of simulation result based on climate scenario is shown in Table 3.

Table 3 shows that in the medium-term scenario, there will not be significant impact of climate change on discharge, it will changes only in the range 0.02-0.20 m^3/sec. The average discharge of scenario II of medium-term is higher than average discharge of scenario I. It is because in scenario I the evapotranspiration is higher than that in scenario II. However, the long-term scenario shows significant effect of climate change since the average discharge increases by 7.8 m^3/sec in the scenario I and decreases by 5.02 m^3/sec in the scenario II.

SIMULATION OF RESERVOIR OPERATION

To determine the energy that can be generated and the associated reliability corresponding to different scenarios of climate change, two steps were followed. The first step is determining the firm power that can be generated by the hydropower plant. Second is simulating the operation of the reservoir with given firm power to determine the amount of energy that can be generated and the associated reliability.

After knowing the firm energy that can be generated by hydropower plant, the next step is simulation of reservoir operation to determine reliability with which different amounts of energy can be generated. The result of reservoir simulation to determine possible firm energy that can be generated is shown in Table 4. This table shows that the possible firm energy that can be generated by Wonogiri hydropower plant is almost the same in medium term but in the long-term scenario I, significant increase in firm energy / firm power is possible.

Figure 3 shows the monthly energy generated and associated reliability. It can be seen that for medium-term scenario, the deviation of reliability of monthly energy generated is less from the observed flow scenario than in long-term scenario even from scenario I or scenario II. Note that for reliability values above 0.90, power generation is likely to be the same in almost all scenarios, except in long-term scenario I that shows higher reliability than the other scenarios. The deviation among the curves increase when the energy generation is less than 4300 MWh. Small deviation in power generation means that the climate change does not give much impact on variation of discharge that have been generated, so the energy that can be generated using the inflow discharge corresponding to climate change is nearly the same with observed period. We may highlight that the possibility of operating the power plant at such low reliability is rather small.

Based on climate change projections and the recommendation of IPCC (2007), there will be small change in precipitation and temperature in the study area in the medium-term scenario. For this scenario, the firm energy that can be generated by hydropower plant is likely to change by 0.3% to -0.33% respectively for scenario I and scenario II. For long-term scenario, there will be significant change in precipitation and temperature and the firm energy is likely to change by 5.03% and 0.85%, respectively for scenario I and scenario II.

Table 3. Statistical Description of Simulation Results Based on Climate Scenario

Parameter	Scenario									
	Observed Year		Medium Term 2024-2043				Long Term 2074-2093			
	1984-2003		Scenario I		Scenario II		Scenario I		Scenario II	
	Discharge (m^3/sec)	Precip. (mm)	Discharge (m^3/sec)	Precip. (mm)	Discharge (m^3/sec)	Precip. (mm)	Discharge (m^3/sec)	Precip. (mm)	Discharge (m^3/sec)	Precip. (mm)
Mean	53.36	5.63	53.38	5.72	53.56	5.51	61.16	6.15	48.34	5.18
Standart Deviation	55.31	13.53	55.73	13.77	55.05	13.25	61.18	14.79	48.75	12.46
Max.	267.02	232.00	267.69	236.64	264.56	225.04	288.30	250.56	230.48	204.16
Min.	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean Dry Month	18.25	2.39	17.99	2.43	18.63	2.37	22.26	2.42	17.80	2.11
Mean Wet Month	102.52	10.20	102.94	10.38	102.46	9.96	115.62	4.84	91.10	4.03
>100	51	49.00	51	55.00	51	46.00	62	92.00	43	33.00
<10	74	30357.0	76	30417.0	72	30582.0	67	30205.0	73	30819.0
Mean Temperature (°C)	25.16		27.17		25.29		28.93		28.93	
Mean Potential Evaporation (mm)	177.73		189.14		178.33		199.20		199.27	
Mean Evapotranspiration (mm)	51.333		53.572		48.148		50.607		50.124	
Scenario										
Precipitation (%)										
DJF	Observed		+2		-3		+8		-12	
MAM	Observed		+3		0		+12		-1	
JJA	Observed		0		-1		+9		-3	
SON	Observed		-1		-3		+9		-9	
Temperature (°C)										
DJF	Observed		+2.25		-0,1		+3.92		+3.92	
MAM	Observed		+2.32		+0.4		+3.83		+3.83	
JJA	Observed		+2.13		-0.5		+3.61		+3.61	
SON	Observed		+1.32		+0.7		+3.72		+3.72	

Table 4. Possible Firm Energy and Corresponding Firm Power of Wonogiri Project

Scenarios		Annual Reservoir Inflow		90% Dependable Flow (m^3/sec)	Possible Firm Energy (MW-hr)	Correspon-ding Firm Power (MW)
		Maximum (MCM)	Standard Deviation			
1984 - 2003		267.02	55.31	0.185904	2314.58	3.21
2024 - 2043	Scenario I	267.69	55.73	0.08224	2321.40	3.22
	Scenario II	264.56	55.05	0.115504	2306.87	3.20
2074 - 2093	Scenario I	288.30	61.18	0.163185	2431.04	3.38
	Scenario II	230.48	48.75	0.113033	2334.18	3.24

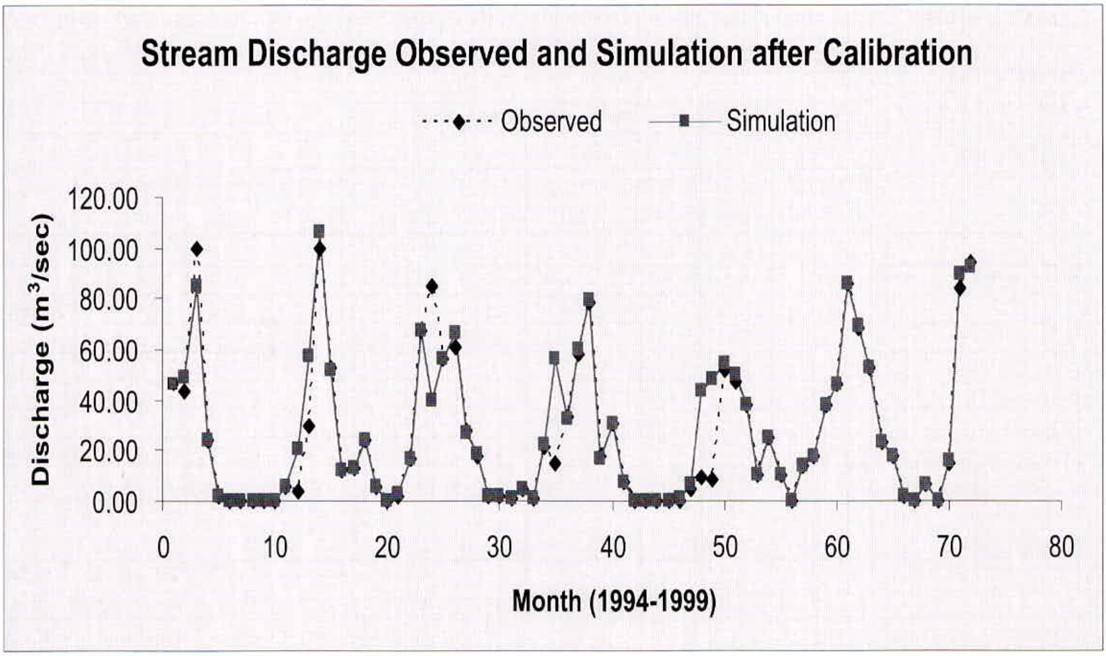

Fig. 3. Observed and Simulated flow after Calibration

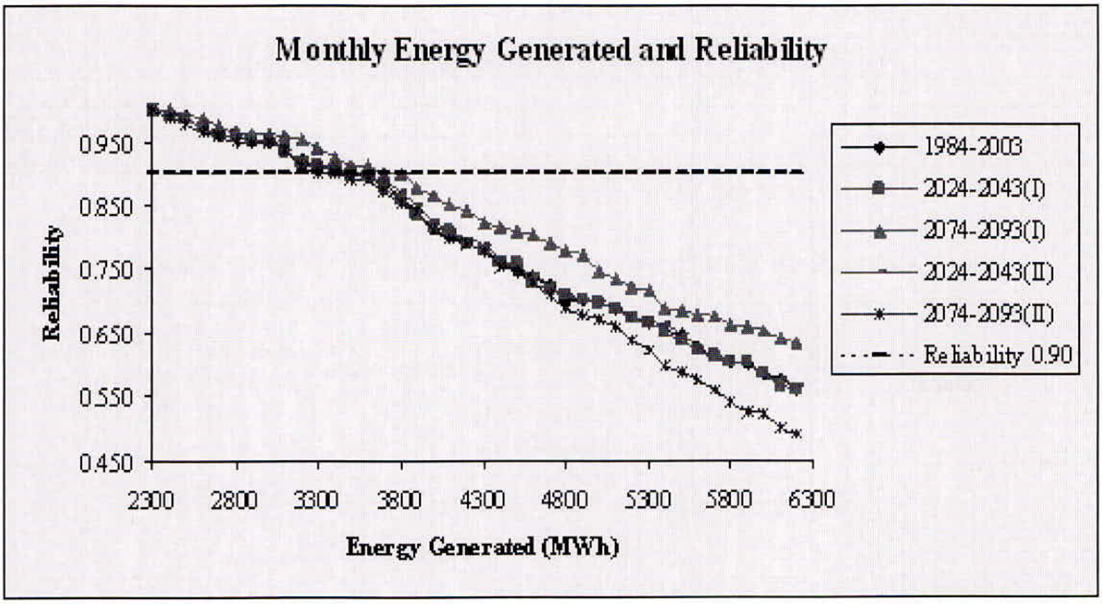

Fig. 4. Monthly Energy Generated and Reliability

CONCLUSIONS

This study has analyzed the response of Wonogiri watershed due to changes in climate and the impact on hydropower generation. The result of modeling of Wonogiri catchment using SWAT model shows that in the medium-term period the discharge is not expected to change much compared to the long-term period. In the medium-term scenario, the firm energy that can be generated by Wonogiri hydropower plant is likely to change by 0.3% to -0.33% respectively for scenario I and scenario II. While it is likely to change by 5.03% to 0.85% respectively for long-term scenario I and scenario II respectively.

From the results of simulation, one can conclude that due to change in climate, hydropower generation may increase or decrease depending on the study area. Thus, climate change impact need not always be negative; these may also be positive.

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