DEVELOPMENT OF INTEGRATED WATER RESOURCES MANAGEMENT PLAN FOR EASTERN DRY ZONE IN SRI LANKA: THE CASE OF GAL OYA RIVER BASIN

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ABSTRACT

The eastern dry zone of Sri Lanka has been devastated frequently by floods and droughts due to significant variations in annual climates, unpredictable rainfall patterns, conventional dam operational rules, and lack of evidence-based information for policy measures for effective water resource management. This study has developed a holistic and end-to-end approach including scientific, engineering, and economic assessments to obtain the evidence-based information for Integrated Water Resource Management (IWRM) and policy implementations in an important river basin (i.e. Gal Oya) in the eastern dry zone of Sri Lanka. This study evidently proved that the wet- and flood-conditions increased during the past (1976-2018) and will continue to increase in the future (2040-2059) under RCP 8.5 scenario, whereas dry-spell decreased in past and will continue the same trend in the future climate in this river basin. The calibrated Water and Energy Budget based Rainfall-Runoff-Inundation (WEB-RRI) model was used to estimate the inflow of Dam Operation Model (DOM) to optimise the economic benefit of agriculture and hydropower productions for wet and dry years. For effective dam operations, the short-term season (wet, dry or normal months) can be predicted reasonably well using Multiple Linear Regression (MLR) equation with the input of forecasted climate indices. For long-term IWRM, long-term (2040-2059) future climate model outputs were used to optimize the dam operation (i.e. minimize the flood and drought conditions and maximize the agriculture and hydropower productions). Finally, the flood disaster risk reduction policy proposals were suggested using the Pressure and Release (PAR) model. This study provided evidenced-based information on present and future climate, water resources, and disaster management issues. It also performed engineering and economic assessments and proposed effective management and mitigation practices and policy recommendations for implementing IWRM in this basin.

Keywords: WEB-RRI, Climate Indices, Dam Optimization, Multiple Liner regression, DOM

INTRODUCTION

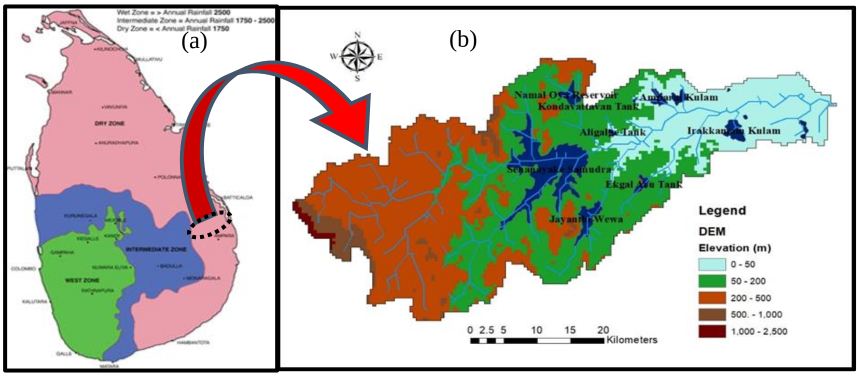

Figure 1: Location of Gal Oya River Basin
(a) Agro-ecological Zones, (b) Gal Oya River Basin

As shown in Figure 1(a), Sri Lanka is divided into three major climate zones: wet, dry, and intermediate zones depending on the annual rainfall. The wet zone receives the annual mean rainfall of 2500mm. The intermediate zone gets in the range of 1750mm to 2500mm, and the dry zone receives less than 1750mm (Punyawardena, 2007). The dry zone of Sri Lanka

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contains almost 75% of Island's land surface. The eastern dry zone mainly depends on the agriculture-based economy. It contributes nearly 25% of the total country's paddy production while approximately 45% population are engaging in agriculture. Floods and droughts are the frequently occurring disasters in the eastern dry zone due to climate change and the uncertainty of weather patterns in Sri Lanka. According to the IPCC (2001), the air temperature of Sri Lanka increased by 0.003 °C per year. Nevertheless, for the last ten years period from 1987-1996, it is 0.025°C per annum. This drastic temperature variation reflects considerable changes in the climate conditions of Sri Lanka, particularly in the eastern dry zone. The Gal Oya River basin (Figure 1(b)) located in the eastern dry zone and the Senanayaka reservoir, which is the largest reservoir in Sri Lanka, is located in the river basin. It has a storage capacity of 950 MCM and can supply to an irrigable area of 90,000 acres. Besides, this reservoir contributes to 11MW of electrical power production to the national grid. The river basin has been severely devastated by the floods and droughts in the past. 2011 and 2014 were the severest flood years that brought catastrophic damages to the people and the property. Subsequently, 2016 and 2017 were recorded as severe drought years and damaged 55% of agriculture productions (FAO, 2017). Furthermore, the conventional dam operation rule is also causing disasters in the river basin.

THEORY AND METHODOLOGY

This study was conducted as a holistic and end-to-end approach, including scientific, engineering, and economic assessments to obtain the evidence-based information for IWRM plan and policy implementation in the Gal-Oya River basin in the eastern dry zone. As shown in Figure 2, the study included six major components: a) Climate change analysis to investigate the trend and severity of floods and droughts in the past and future climates; b) Hydrological modelling to study the hydrological responses of the basin for the past, future climate variation and effective dam operations; c) Dam optimization for wet and dry years to optimize the economic benefit of agriculture and hydropower productions in wet and dry years; d) Short-term seasonal prediction to find a relationship with rainfall pattern and dominating seasonal climate indices of Sri Lanka; e) Long-term dam optimization for future climate change to plan a long-term future (2040-2059) dam operation by mitigating the flood, drought and maximize the agriculture and hydropower productions; f) Disaster risk assessment and policy implication to propose policies to mitigate the present and future climate disasters, and enhancement of IWRM.

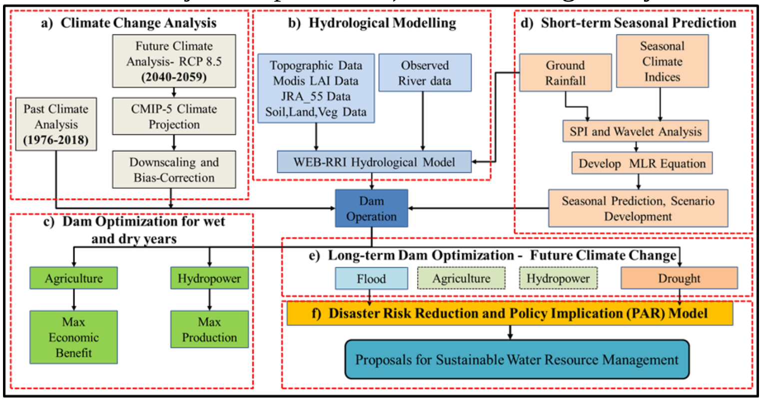

Figure 2: Overall Methodology

a) Climate Change Analysis

Firstly, the past climate was analyzed for two periods from 1976-1996 and 1997-2018 to examine and verify the climate signals. Then, the future climate was analyzed using the CMIP-5 and climate change projection tool of Data Integration & Analysis System (DIAS) from 2040-2059. The climate data were selected according to the regional performances and bias-corrected by means of observed rainfall data from 1981-2000. Then the future climate of 2040-2059 was projected for RCP 8.5 scenario.

b) Hydrological Modelling

WEB-RRI hydrological model, developed by Rasmy et al. (2019), was employed to study the hydrological response of the basin for present and future climate. This model is capable of estimating soil moisture, evaporation, groundwater, and inundation. The necessary data: topographical data, Modis LAI data, Japan Reanalysis-55 years data, soil, land, vegetation data, and observed rainfall data were prepared and input into the model. Then, the model was calibrated and validated and the model performance was evaluated using indexes: Mean Bias Error (MBE), Root Mean Square Error (RMSE) and Nash-Sutcliffe efficiency (NSE).

c) Dam Optimization for Wet and Dry years

DOM was developed to optimize the agriculture and hydropower by considering the reservoir water balance, CLIMWAT and CROPWAT software for irrigation practice (Smith et al., 1991). The performance of DOM was verified for wet and dry years. The potential scenarios and several viable options were created and investigated. Finally, the best option was selected for each wet and dry year to optimize the benefit of agriculture and hydropower.

d) Short-term Seasonal Prediction

The Standard Precipitation Index (SPI) and wavelet analysis were conducted to predict the short-term seasonal prediction to optimize the dam operation. This study aimed to find a relationship with rainfall pattern and seasonal climate indices such as Indian Ocean Dipole (IOD), ENSO, El Nino Modoki, and Madden-Julian Oscillation Index (MJO). These indices were assumed as the dominating indices for the climate of Sri Lanka depend on previous studies. The wavelet coherence analysis was performed to find the major dominating climate indices among them. The developed relationships were employed to predict the wet and dry years.

e) Dam Optimization for Long-term Future Climate Change

The dam optimization for long-term future climate (2040-2059) analysis for policy implication is essential to mitigate the flood and drought. Hence, the selected seven out of 44 Global Circulation Model's (GCM) future discharges were simulated using WEB-RRI model, and the results were analyzed. The dam optimization was employed to mitigate the flood and drought and maximize the economic benefit of agriculture and hydropower in future based on the case of an extreme scenario model.

f) Disaster Risk Reduction and Policy Implication

The vulnerability assessment was made using the PAR mode (Wisner et al., 2004) to assess the disaster risk of the river basin. This model identified the root causes, dynamic pressure, and unsafe condition based on the socio-economic, political, environmental condition of the river basin. Then, the flood disaster risk reduction policies were suggested pertaining to the study results and social, economic conditions of the river basin to enhance resilient to flood disaster and increase the economic benefits.

DATA

The rainfall data for the eastern dry zone and Gal Oya river basin were collected from the Irrigation Department and Metrological Department. Long duration daily rainfall data of 118 years and 33 years were gathered to study the eastern dry zone for Trincomalee and Batticaloa districts respectively, while monthly data of 118 years were collected for Ampara district. In the Gal Oya River basin, the Bibile station has more than 100 years of daily rainfall data are available. Besides, Mapakedewewa, Maha Oya, and Navagiri locations have more than 20 years of daily rainfall data. At other stations, only a few years of data are available.

RESULTS AND DISCUSSION

The results obtained from six major methodological components are discussed in this section.

a) climate change analysis: The past-observed rainfall from the year 1976 -2018 was analyzed into two periods: 1976-1996 and 1997-2018, and the results of annual numbers of wet days with a rainfall of more than 1 mm and annual numbers of rainy days more than 50 mm were obtained. In addition, wet spells and dry spells were analyzed. The wet and dry spells study consisted of short (0-5 days), medium (5-10 days), and long (more than 10 days) spells. Then the innovative trend analysis was employed to analyze the extreme rainfall for both time intervals. The uniformity results were obtained for both past time intervals and analysis revealed that: the number of rainy days per year is increasing; extreme rainfall is increasing; all types of wet spells (short, medium, and long) are increasing; and long dry spell is decreasing. The results expressed a clear sign of an increasing trend of wet- and flood-conditions and a decreasing trend of dry conditions over the past years. Then, the seven GCMs: ACCESS1.0, CESM1 (BGC), CNRM-CM5, CSIRO-Mk3.6.0, CanESM2, GFDL-ESM2G and IPSL-CM5A-LR were selected from out of 44 GCMs of CMIP-5 models. The projected rainfall from the GCMs for the future climate (2040-2059) was bias-corrected using in-situ data of 1981-2000. The bias-corrected future climate rainfall data was also analyzed as similar to past rainfall data analysis. The results revealed that: monthly average rainfall will increase; extreme rainfall will increase; rainfall will increase with return period; medium and the long wet spells will increase; and all dry spells (short, medium, long) will decrease. So, both analyses of past and future events pointed out the consistent results and brought sound information of increasing trend of flood and decreasing trend of drought.

b) Hydrological modelling: Figure 3 compares the observed daily discharges with WEB-RRI model simulated discharges for model calibration. Several parameters, such as topography, soil, and river parameters, were adjusted to match the ground observed discharge. In this case, the duration of

01/01/2015 to 31/05/2015 was used for calibration. The model was well calibrated during high flow and low flow values. The discharge location was Igniyagala, near the spill of the Senanayake reservoir. The WEB-RRI hydrological model responded to both wet and dry seasons perfectly. The calibration results

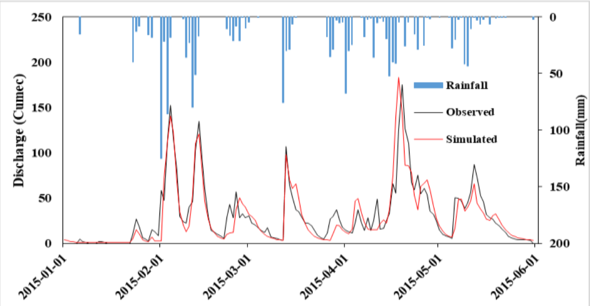

Figure 3: Calibration of WEB RRI Model

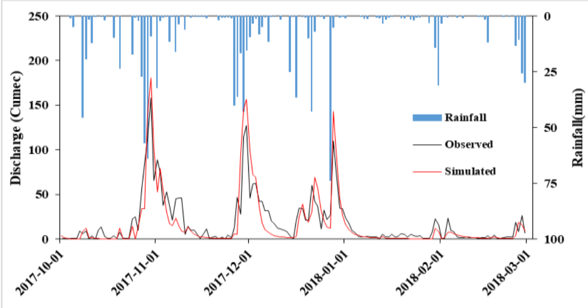

Figure 4: Validation of WEB RRI Model

of the model performance indexes indicated a good agreement values of MBE = -1.47m^3/s, RMSE= 14.87m^3/s, and NSE = 0.78. Then, the calibrated WEB-RRI hydrological model was employed for the validation run from 01/10/2017 to 31/02/2018 as shown in Figure 4. The model had sensed even the small peaks, which is less than 10 m^3/s. Finally, the model performance indexes were obtained with good agreement values of MBE = -1.94m^3/s, RMSE= 14.54m^3/s, and NSE = 0.72.

c) Dam optimization for wet and dry years: The formulated DOM was verified for wet and dry years with observed dam storage as shown in Figure 5 and Figure 6. The simulated values indicate a good agreement with NSE value of 0.82, 0.87 for wet and dry years. Then, DOM was used to optimize the economic benefit of agriculture and hydropower during wet and dry years.

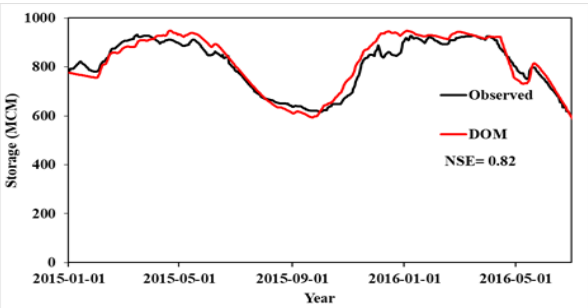

Figure 5: DOM verification – Wet Year

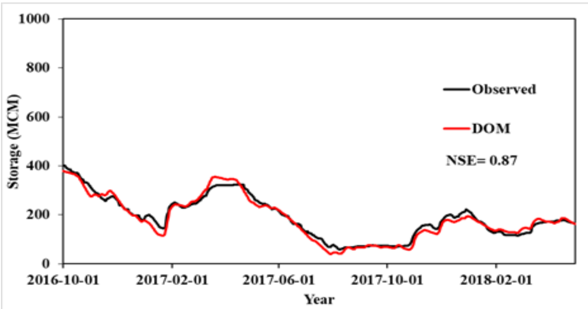

Figure 6: DOM verification – Dry Year

The possible scenarios were created for the wet and dry years to optimize the dam operation in case of agriculture and hydropower. The most possible scenario for the wet year will be the changing the cultivation calendar and the dry year will be changing the cultivating crop type. The Maha (Rainy) cultivation is engaged from 15th October to 15th February, while Yala cultivation from 15th April to 15th August in the Gal Oya River basin. The scenario-1(changing cultivation calendar) was analyzed in the year 2015 with viable options of moving cultivation calendar forward and backwards by 15 days, 30 days and 45 days. The scenario-2 (changing cultivation crop type) was analyzed in the year 2016 with

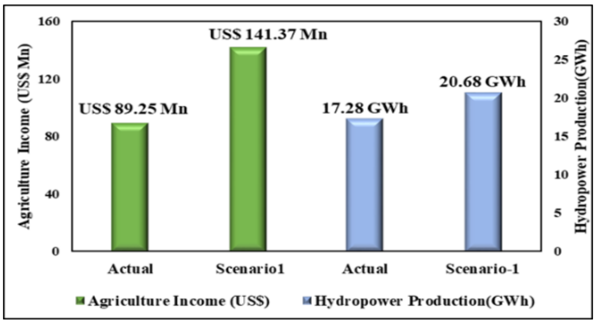

Figure 7: Economic Benefit Analysis – Scenario-1

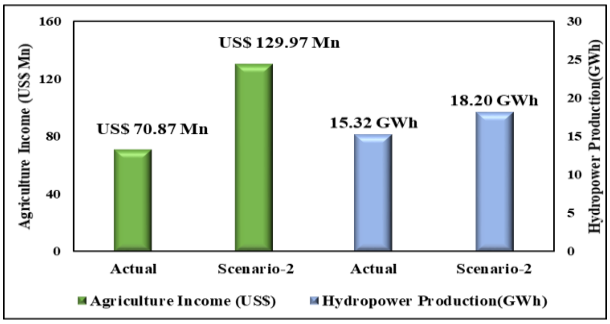

Figure 8: Economic Benefit Analysis – Scenario-2

probable options of changing cultivation crop by 60% Paddy + 40% Green Gram, 90 days Paddy and 50% of 105 days Paddy + 50% of 90 days paddy. Then, moving the cultivation calendar by 30 days ahead for the wet year and for the dry year by changing the crop type as 60% of Paddy + 40% of Green Gram were identified most effective methods for minimizing the water usage of agriculture and maximize the reservoir storage relative to the other alternatives. Figure 7 illustrates the comparison between the actual and Scenario-1 of economic benefit. If the Scenario-1 was incorporated in the wet year 2015, total revenue from agriculture and hydropower could have been risen by 58% and 20% respectively. Similarly, in Figure 8 if the Scenario-2 was adopted in the dry year 2016, total revenue from agriculture and hydropower could have been risen by 83% and 19% respectively.

Table 1: Wavelet Coherence Analysis

Station	Mode of Variability	IOD	ENSO	El-Niño Modoki	MJO
Trincomalee	2-4	51.70	51.96	51.71	51.11
	4-8	51.44	52.06	51.43	56.33
	8-16	55.78	57.15	55.78	54.06
Ampara	2-4	51.39	53.54	52.97	53.24
	4-8	50.20	52.13	50.86	57.07
	8-16	53.42	55.34	56.55	52.09
Batticaloa	2-4	53.56	53.82	51.00	55.49
	4-8	52.10	50.31	50.11	56.00
	8-16	56.80	52.79	62.67	55.40

Table 2: Multiple Linear Regressions Equations

Sign of Indices					MLR Equation to predict SPI	Pearson R	Satisfied % of Wet, Normal and Dry Condition at Calibration (1999-2018)	Satisfied % of Wet, Normal and Dry Condition at Validation (1978-1998)
No	IOD	ENSO	MODOKI	MJO				
1	+	+	+	+	-0.43 -0.43*IOD+0.96*ENSO-0.78 MODOKI+0.38*MJO	0.71	73%	71%
2	+	+	+	-	0.40 -0.92*IOD+1.08*ENSO-1.89 MODOKI+0.78*MJO	0.53	78%	80%
3	+	+	-	+	-1.28 +0.32*IOD+0.08*ENSO -0.67* MODOKI+0.18* MJO	0.61	92%	77%
4	+	+	-	-	-0.81+0.32*IOD+0.15*ENSO -0.62* MODOKI - 1.88* MJO	0.52	83%	71%
5	+	-	+	+	1.90+0.71*IOD+0.12*ENSO -6.63* MODOKI - 1.87* MJO	0.53	85%	67%
6	+	-	+	-	-0.37-0.92*IOD - 0.48*ENSO + 1.48* MODOKI – 0.27* MJO	0.48	91%	70%
7	+	-	-	+	-0.93+0.23*IOD - 0.36*ENSO – 0.62* MODOKI + 1.30 *MJO	0.77	93%	78%
8	+	-	-	-	-0.57+2.97*IOD - 0.19*ENSO – 0.50* MODOKI + 0.16*MJO	0.50	86%	33%
9	-	+	+	+	-2.02 -0.64*IOD +1.91*ENSO – 0.63* MODOKI + 2.02*MJO	0.97	83%	65%
10	-	+	+	-	1.35 +2.57* MODOKI + 7.13*MJO	0.95	95%	50%
11	-	+	-	+	-1.57 + 2.23*IOD -0.09*ENSO – 1.83* MODOKI + 0.96*MJO	0.96	100%	95%
12	-	+	-	-	0 possibility for last 40 years	-	-	-
13	-	-	+	+	-0.41 + 1.13*IOD -0.01*ENSO – 2.80* MODOKI + 0.96*MJO	0.51	70%	60%
14	-	-	+	-	2.17 + 1.71*IOD +2.71*ENSO – 0.82* MODOKI + 0.56*MJO	0.98	100%	40%
15	-	-	-	+	0.67 – 0.71*IOD -0.40*ENSO +1.12* MODOKI – 1.59*MJO	0.51	64%	55%
16	-	-	-	-	0.51 – 2.03*IOD +0.07*ENSO +2.1* MODOKI – 1.15*MJO	0.91	100%	52%

d) Short-term seasonal prediction: SPI and wavelet analysis were conducted to find a relationship with rainfall pattern and seasonal climate indices for short-term seasonal prediction study. As shown in Table 1, the wavelet coherence analysis revealed the sound results that all the assumed climate indices are moderate coherence in all districts. Then, the MLR equations were developed based on the past pattern of SPI and climate indices as illustrated in Table 2. The forecasted values of future months' climate indices are available in relevant metrological organizations (JMA, JAMSTEC or NOAA). Therefore, the SPI values of future months can be predicted using the developed MLR equations. Finally, the short-term seasonal prediction can be made as wet, dry or normal month.

e) Long-term dam optimization for future climate change: The simulated results of the selected seven GCMs projected that the river basin undergoes significant discharge changes during future (2040-2059) and monthly average discharge also varies significantly. Further, the IPSL-CM5A-LR produced higher extreme discharge compared to other GCMs. In order to cater the future catastrophic disasters, DOM was applied with an extreme scenario by assuming that the similar prevailing cultivation pattern will continue in future with 90,000 acres in Maha (rainy) season and 60,000 acres in Yala (dry). Figure 9 indicates the reservoir capacity variation and spillage amount throughout the future climate period of 2040-2059 without optimizing dam operation. The above results

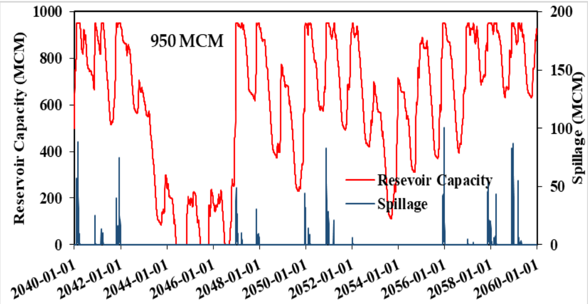

Figure 9: Dam Capacity Variation without Optimization

Table 3: Economic Benefit by Pre-Release of Dam

Pre- Release of the Dam		Amount (Cumec)	Additional Agriculture Income Mn US$	Additional Hydropower Production in MWh
From	To			
2040-01-01	2040-06-31	30.0	13.12	17,280
2040-07-01	2041-12-31	17.5	10.5	26,250
2046-06-01	2047-03-31	17.5	7.87	13,100
2047-10-01	2047-12-31	17.5	-	4,380
2049-08-01	2049-12-31	23.5	10.5	10,950
2050-01-01	2050-03-31	30.0	-	8,740
2055-05-01	2055-12-31	30.0	13.12	23,330
2056-06-01	2058-05-31	17.5	26.25	35,000
2058-06-01	2059-12-31	30.0	15.75	52,800
Annual Additional Benefit			**4.85**	**9,500**

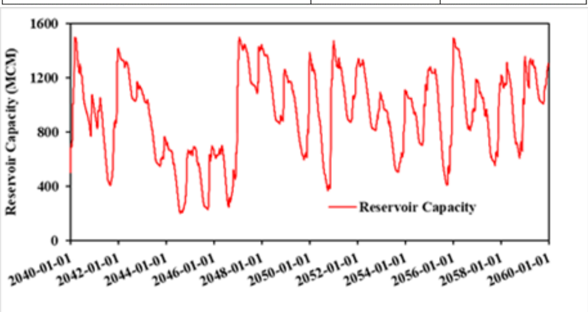

Figure 10: Dam Capacity Variation after Optimization

emphasize that there shall be frequent spillages due to the higher inflow to the dam and its capacity will significantly decline during the years of 2043-2046 due to severe drought conditions. If the dam is operated in the existing condition, the river basin will experience severe floods and droughts in future. To cater to the flood and drought condition, the remedial measures such as raising the dam capacity from 950 MCM to 1500 MCM and pre-release of water were investigated. Results showed these countermeasures can be effective and thus flood and drought events can be mitigated as shown in Figure 10. If the pre-release scenario is implemented as per Table 3, the annual additional agriculture income will be US$4.85 million, and annual additional hydropower production will be 9500 MWh.

f) Disaster risk assessment and policy implication: A systematical policy implication is key by assessing disaster risk to prevent future flood and drought disasters. For that purpose, the vulnerability assessment was made using the PAR model, based on the socio-economic conditions of the river basin. Then, the relevant policies were suggested depends on the research output. The recommended policies are; 1) best priority for flood mitigation projects, 2) change the cultivation calendar for wet year prediction, 3) change crop type for dry year prediction, 4) dam capacity should be increased to cater the future flood, 5) pre-released water should be effectively utilized in future condition, 6) install rainfall and discharge measuring gauges, 7) spill tail channel capacity should be improved.

CONCLUSION & RECOMMENDATION

The holistic and end-to-end approach of this study highlighted the concrete evidence that river basin will experience wetter climate in the future with intensified and frequent floods, whereas the drought impacts will be reduced. The WEB-RRI hydrological model showed good performance for estimating basin hydrological responses. It was proved that DOM can be effectively employed to optimize the dam operation for predicted wet and dry years by shifting cultivation calendar and changing the crop type. This study also reveals that the four climate indices such as IOD, ENSO, El-Nino Modoki and MJO have great coherence with rainfall in the river basin. Therefore, multiple linear regression equation can be used effectively to predict the seasonal climate condition (wet, dry or normal), using the forecasted seasonal climate indices. The effect of long-term future climate (2040-2059) with extreme scenario can be optimized by the dam pre-release operation and raising the dam storage capacity. Finally, this study also summarized the essential policy implications based on this research outputs to enhance the climate change mitigation and adaptation measures to improve the IWRM plan for Gal Oya River basin and the eastern dry zone. This study provides complete evidence-based solutions to existing and future climate change issues and water resources management problems. Therefore, the suggested policy recommendations of the study should be applied in all levels of administration system in the river basin to mitigate the flood and drought and maximize the economic benefit of agriculture and hydropower in the present and future contexts.

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