Assessment of Hydrologic Alteration due to Hydropower Reservoir Operation System

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Abstract : The alteration in river flow regimes by human activities is a key impact on riverine ecosystem. This study focus to check how flow regime was changed from natural flow due to reservoir operation systems. HEC-ResSim model was used to simulate the reservoir system under the alternative scenarios and RVA analysis by 33 indicators of hydrologic alteration was used for the determination of flow regime alteration. To investigate the flow alteration analysis, the case study is Myitnge river downstream from Yeywa hydropower reservoir. The alteration analysis was done by the reservoir operations under the existing policy and under the environmental flow restriction. The existing operation system leads to moderately change in the natural flow regime. When the environmental flow constraint was considered in the operation system, the hydrologic alteration degree could be reduced by 5.73 % and moreover the power production was becoming increase to 1.3 % than the existing production. The result indicates that the reservoir operation system that provides the environmental flow can perform the closet natural flow regime for the ecosystem integrity while increasing the energy generation**.**

***IndexTerms* - Hydrologic alteration,HEC-ResSim,environmental flow,RVA,Myitnge river.**

I. INTRODUCTION

Rivers and streams have seasonally variable patterns in their flows of water, sediment and nutrients for freshwater ecosystem. Water development projects such as dam, weir and estuary barrage for the purposes of flood control, energy production, irrigation, water supply and navigation can directly effect on the hydrological regime. These activities for human survival can cause the alteration in the natural flow pattern and the changes on water quality, quantity, temperature, sediment, and nutrient and floodplain environment. Due to blocking of the river flow, the upstream and downstream longitudinal connectivity are lost and mainly, it occur the loss of flood. Later connectivity between the river and floodplain are diminished due to loss of flood [2]. Hydrological alterations can cause the stress on the stream heath and the loss of ecosystem service. As a consequence, the river is becoming thirsty and it leads to the degradation of the river health. Globally, hydrologic alteration is threating the freshwater biodiversity and ecosystem integrity.

Most of the hydrological alterations observed in Myitnge river are due to hydroelectric production. When the power demand is becoming more and more, many reservoirs are planned to build along Myitnge river to meet the power demand. Therefore, changed stream flow regime related to hydropower production of the plants is becoming the critical threatening for Myitnge river. In the storage type reservoir, the flooded water is stored in the rainy season and subsequently released after generating the power in the non-rainfall season when the inflow is low. Because the hydropower plants generate electricity to meet the variable demand, the released flow has highly variable. Such pulses of water can significantly alter the quantity, velocity, temperature of water and cause water level fluctuation in the downstream. Hydropeaking can rapidly change the river hydrology and give the pressures on aquatic organisms. Furthermore, the degree of streamflow alterations due to reservoirs operation can change over time according to the variable energy demand by timely. Improvement of reservoir operation system is becoming an important sector for the need to safeguarding downstream ecosystem when managing water to meet power production demand.

This study represents the flow regime alteration assessment on the river downstream due to reservoir operation and the determination of the eco-condition of the river at the beginning level according to the quantitative assessment of hydrological alteration. More effective assessment of the impact on riverine ecosystem should be done from predicting, monitoring, and evaluating the responses of environmental water releases, and how environmental water can be delivered to enhance ecological outcomes.

II. DESCRIPTION OF STUDY AREA

Myitnge river (Namtu) is one of the large-scale tributaries on left bank of Ayeyarwady river and it originates from Mount Loi Swang at an elevation of 1460 m on the northern Shan Plateau. The river flows in a generated direction of north-east to south-west and joins the Ayeyarwady river at about 15 km to the south-west of Mandalay. It longs about 530 km and its tributaries are Zawgyi, Panlaung and Nantalan rivers. River basin area is 34800 km^2 and it covers from Mandalay division near the confluence of the Ayeyarwady river to the north-west part of the Shan state. The Yeywa power plant, installed capacity of 790 MW (4x179.5MW) was completed in 2010 and the design energy is 3550 GWh annually. It is located 80 km upstream of the confluence of Ayeyarwady river. The catchment area of Yeywa plant is 28206 km^2. The average annual inflow to the reservoir is about 15231x10^6 m^3 which has gross storage of 2.6x10^9 m^3 and effective storage of 1.6x10^9 m^3. The maximum water level in the reservoir is 185 m above mean sea level. The surface area at maximum water level is 59 km^2. Myitnge river basin is centrally located in Myanmar with a continental climate and river basin is characterized by two seasons, a rainy season from June to October and a dry season from November to May. The mean annual rainfall is about 1400 mm. This study focuses only on the altered flow regime condition in downstream due to Yeywa dam operation. The location map of catchment area in Myitnge river basin including Yeywa power plant is shown in Fig. 1.

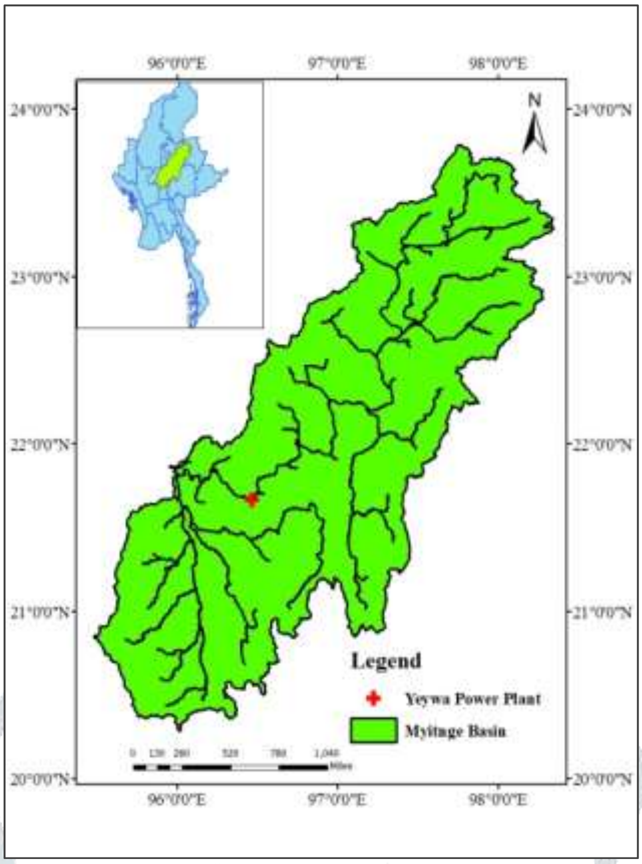
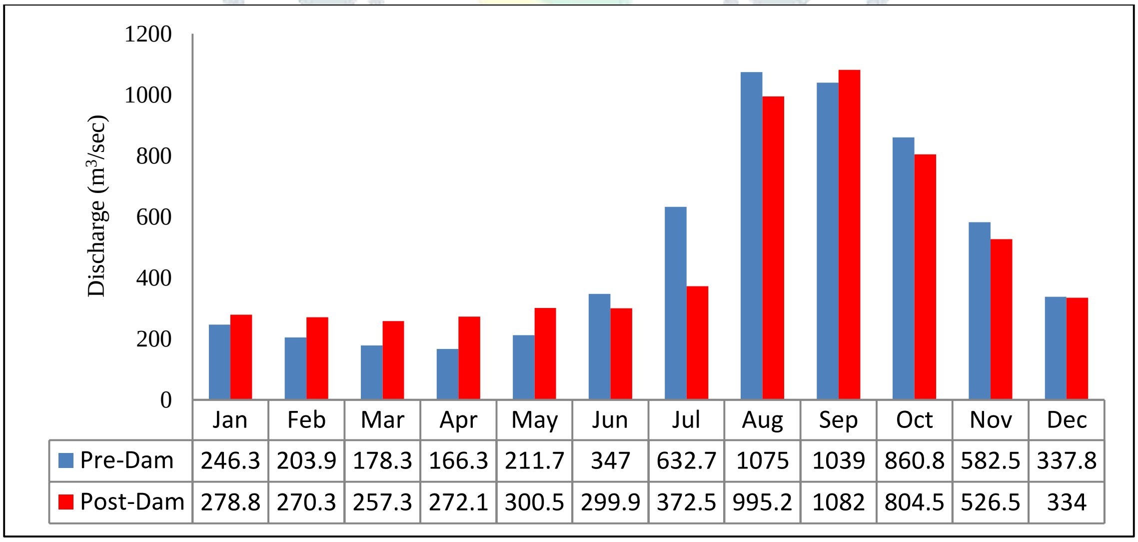


Figure 1 Myitnge River Basin Map Including Yeywa Hydropower Plant

2.1 Availability of Hydrological Data

The flow regime of Myitnge river downstream from Yeywa dam has been altered after 2010 when hydropower dam was completed and operated. In order to analyze the hydrological alteration due to dam operation, pre-dam flow for 29 years (1981-2009) and post-dam flow for 8 years (2011-2018) were used. These data measured at Salin station where it locates just downstream from Yeywa dam were collected from the Department of Hydropower Implementation (DHPI). Due to dam operation, the post-flow regime has the increased water in low flow season and the decreased water in the high flow season except September. In July, the rate of flow changes in post-dam from pre-dam is very large although December flows have nearly the same amount. The mean monthly flows of the pre and post-dam are shown in Fig. 2.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟦 Pre-Dam	246.3	203.9	178.3	166.3	211.7	347	632.7	1075	1039	860.8	582.5	337.8
🟥 Post-Dam	278.8	270.3	257.3	272.1	300.5	299.9	372.5	995.2	1082	804.5	526.5	334

Figure 2 Mean Monthly Flow (m^3/sec) in Myinge River

III.METHODS AND MATERIALS

3.1 Determination of Hydrologic Alteration

Range of Variability Approach (RVA) that is a set of Indicator of Hydrologic Alteration (IHA) was used to analyze the changes between the pre and post development periods. A degree of hydrologic alteration in post dam from pre dam one is determined from 33 indicators of hydrologic alteration [7]. A natural hydrologic time series is used to define the limited and lower boundary for each hydrologic indicator and this range of variation was identified as the flow management target. A range defined by the 25th and 75th percentile exceedance flows of natural historical records has been recommended as the management target [7]. The degree of hydrologic alteration "D" that is the deviation of the post-dam flow regime from the pre-dam one was quantified by the following equation.

$$D_i = \left[\frac{(N_o - N_e)}{N_e} \right] \times 100 \tag{1}$$

Where, D_i is the degree of hydrologic alteration (%) for i^{th} indicator, N_o and N_e are the observed and expected number of post-dam years for which the parameter values fall within the RVA target range. [7]

The mean/single alteration indicator (D) for various parameters was quantified using the following Eq. 2. [7] Table 1 show the five alteration levels; slight, low, moderate, high and severe alteration related to the percentage range of alteration level.

$$D = \left[\frac{1}{m} \sum_{n=1}^{m} D_i^{\,2} \right]^{\frac{1}{2}} \tag{2}$$

Table 1 Classification of Alteration Level

Alteration Level	**Slight**	**Low**	**Moderate**	**High**	**Severe**
D (%)	< 20	20-40	40-60	60-80	>80

3.2 Reservoir Operation System

HEC-ResSim, developed by the Hydrological Engineering Centre of the United States of Army Corps of Engineers (USACE) was used to simulate the operation system at Yeywa Hydropower reservoir. In the model, three zones such as flood control, conservation and dead storage are defined. As a model default, the guide curve (rule curve) is defined as the upper boundary of the conservation zone and under the minimum water level is the dead storage zone. The model tries to control the reservoir level according to the guide curve by obeying the operational rules and constraints defined in each zone. In model simulation, the operation is done using the net inflow obtained after deducting the water used for power production, spill, evaporation and losses from inflow. The design rule curve at Yeywa reservoir is shown in Fig. 3.

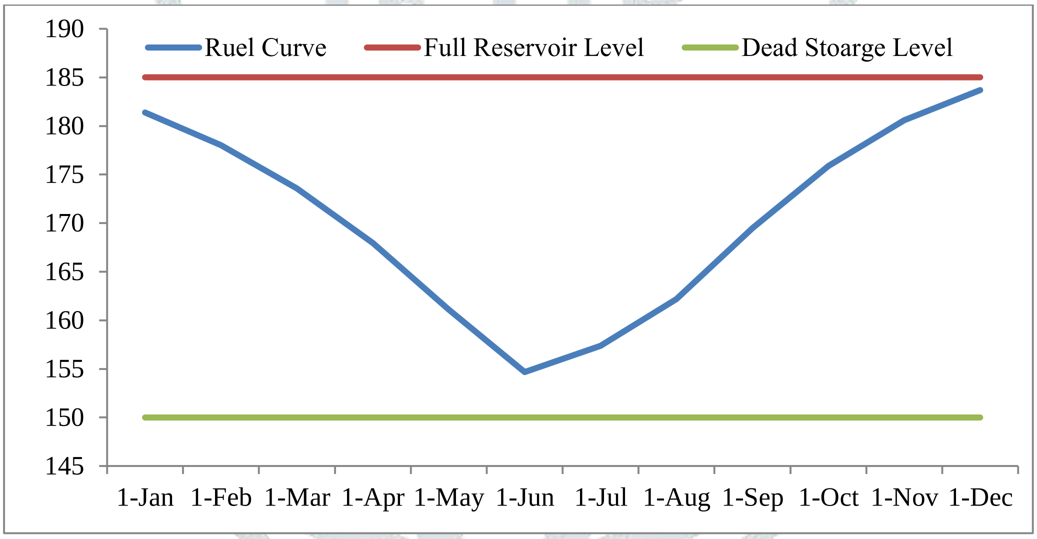


Figure 3 Rule Curve with Full Reservoir Level and Dead Storage Level of Yeywa Reservoir

In this study, the alteration analyses were done by the simulated outflow under the existing operation policy and under the operation with e-flow constraint.

(i) Operation under the existing policy

In the existing condition, Yeywa power plant is connected to the national power grid and it is operated to meet the power demand in the region. Riparian release is defined as the minimum 100 m^3/sec. This simulation was conducted to check the model performance and to define as the base case for the comparison analysis with alternative scenario.

(ii) Operation considering the minimum environmental flow requirement

The operation was done to generate the power considering the environmental flow (e-flow) restrictions. The operational e-flow constraint is such that the release flow should not be less than the recommended minimum environmental flow. Tessman method was used to evaluate the minimum e-flow requirement by monthly basic.

3.3 Environmental Flow

Environmental flows refer to water for healthy ecosystem and provide critical contributions to river health, economic development and poverty alleviation. Environmental flows are one tool in managing the impacts of hydropower dams, from social perspective, a choice among multiple levels of ecosystem protection. A variety of methods have been developed for setting environmental flow. Each method has its strength and weakness and requires varying levels of effort. Tharme (2003) and Tharme and Smakhtin (2003) prefer to categorize the methods into four categories_ hydrological, hydraulic, habitat simulation (rating) and holistic methods.[1] In this study, Hydrological method was applied for the initial stage on setting the environmental flow for Myitnge river. Under the category of hydrological methods, Tessman method was applied using the historical flow of pre-dam period (1981-2009) to recommend the environmental flow.

Tessman method gives the minimum environmental flow threshold as the variable flows by monthly basic. This method is simple and based on the single flow data, unnecessary field work. In order to define the environmental flow, the following guidelines were used.

1. MMF, if MMF < 40% MAF
2. 40% MAF, if 40% of MAF< MMF< 100%MAF
3. 40% MMF , if MMF > MAF

Where, MAF is mean annual flow and MMF is mean monthly flow. [1]

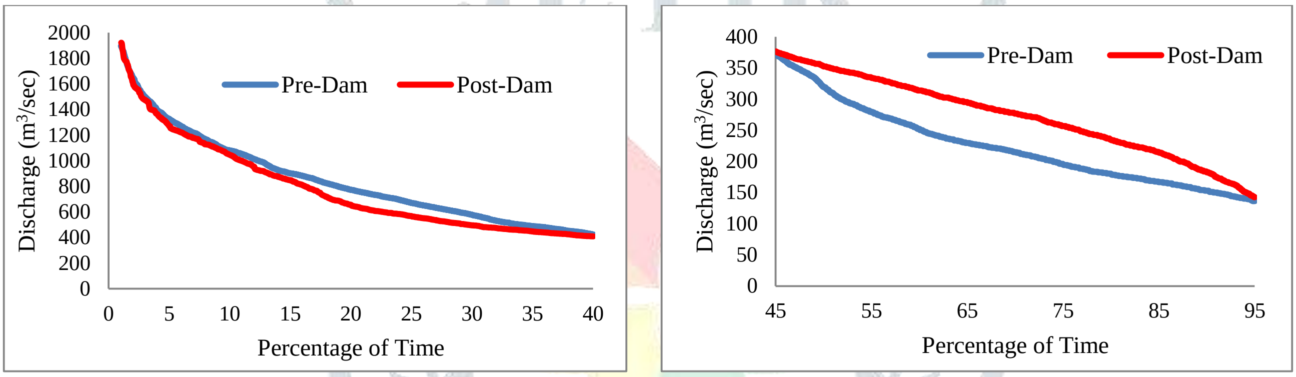
IV. RESULT AND DISCUSSION

4.1 Impact on Natural Flow Region due to Hydropower Dam Operation

The characterization of the natural varying flow in a river prior to significant human activities provides the flow regime needed for native species and ecosystems. According to this approach, the flow without the human influences represents the ecological base flow to provide the ecosystem integrity. The ecological impact analysis was done by comparing the flow duration curve (FDC) of the pre-dam and post-dam period. The period before 2010 was defined as pre-dam (natural) and after 2010 was defined as post-dam period.

In storage type hydropower reservoir, the water is stored in the rainy season and the stored water is used to provide the power demand in non-rainfall season. Due to such dam operation, the loss of flood in the rainy season occurs along the river downstream. As a consequence, the lateral connection between the floodplain and the river are diminished and it faces to the loss of floodplain and riparian nutrients. Therefore, floods are also one of the important environmental flow components. Fig. 4(a) shows the eco-deficit portion in high flow and flood regime and that portion can give the stresses on the riverine ecosystem.

When the stored water is released after generating the power in non-rainfall period, the low flow regime has more water than the natural flow. Fig. 4(b) shows the eco-surplus portion in the low flow regime and its condition gives the better result for water users but it may also affect to some organisms living only in the low flow nature. For maintaining the closet natural condition for native organisms, the flow regime between pre and post-dam should not significantly alter. These eco-deficit and eco-surplus portions indicate the impacts on the natural river ecosystem due to hydropower dam operation.



(a) (b)

Figure 4 (a) Eco-Deficit in High flow regime and (b) Eco-Surplus in Low Flow Regime due to Dam Operation

4.2 Determination of Environmental Flow Threshold

In order to recommend the environmental flow for freshwater ecosystem, more detailed investigations to the impacts of the dam and its relationship are needed. However, in this study, Tessman method was used to determine the minimum e-flow requirement using the long-term natural historical records (1981-2009). It can give the good result for minimum e-flow threshold at the beginning level. Table 2 shows the minimum e-flow recommendation according to the defined three rules. The mean monthly flow (MMF) of Myitnge river is shown in Fig. 2 and mean annual flow (MAF) is 490.12 m^3/sec.

Table 2 Monthly Minimum Environmental Flow Requirement (m^3/sec)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
E-flow	196.05	196.05	178.32	166.3	196.05	196.05	253.08	429.89	415.76	344.34	232.99	196.05

4.3 Reservoir Operation System using HEC-ResSim

4.3.1 Reservoir Operation under Existing Policy

The purpose of this scenario is to check the model performance and to use the base case for the comparison analysis with the alternative scenario. The simulation was conducted using the input data of daily inflow and daily power production from 2011 to 2018. In this scenario, hydropower time series requirement rule was applied in model. According to this rule, the simulated energy is 2621.61 GWh and observed is 2593.76 GWh annually. Under the existing operation policy, the model performance was checked using the observed and simulated reservoir water level. For this objective, the statistical parameter, namely the squared correlation coefficient (R^2) was quantified and the result was 0.98 as shown in Fig. 5. Therefore the result indicates that HEC-ResSim model could meet the reservoir system to an acceptable limit between the simulation and actual operation.

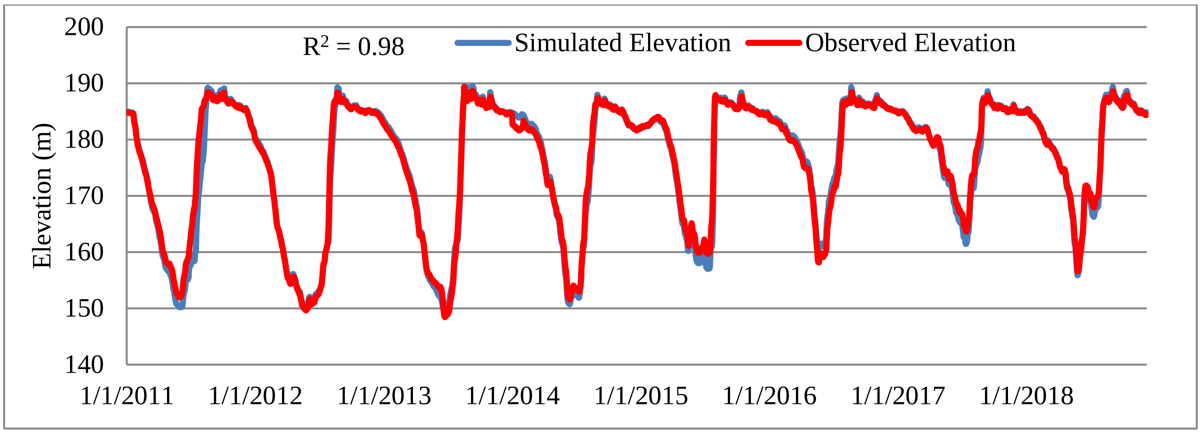


Figure 5 Comparison of the observed and simulated reservoir water level

4.3.2 Reservoir Operation considering the Minimum Environmental Flow Requirement

The reservoir was operated to generate the power with the constraint that the released flow is not allowed to less than the monthly minimum environmental flow requirement. Tessman method was used to determine the minimum e-flow constraint. In this simulation, downstream control function rule for environmental release and hydropower time series requirement rule for power production were used in the model. Among these two rules, downstream control function rule for environmental flow was defined as the first priority. The simulated power production is 2666.312 GWh annually. The result gives an overall 1.3 % increase in the annual power production compared to the existing operation policy. Simulated outflow with the minimum e-flow constraint is shown in Fig. 6.

4.3.3 Result Discussion under Two Reservoir Operations

The simulated outflow conditions under two reservoir operation systems and the minimum environmental flow requirements are shown in Fig. 6.

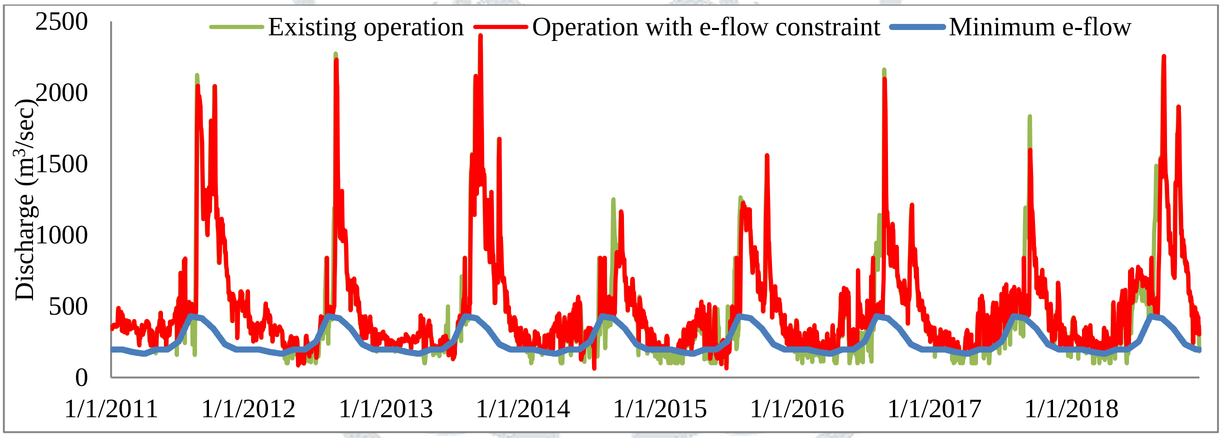


Figure 6 Simulated Outflows under Alternative Reservoir Operation System

In order to support the essential process for the healthy river ecosystem, the released flow should not be less than the minimum e-flow requirement. Under the existing operation policy, the released flow can't provide the minimum e-flow requirement in the period of dry season and early rainy season. When the reservoir was operated with the downstream control function rule to provide the minimum e-flow, the released flow can significantly support the minimum e-flow than the existing case although the operation can't meet the minimum e-flow in a few periods along the simulation long-time series. Moreover this operation can produce the power annually 1.3 % more than the existing production, although the power deficit occurs in December as shown in Table 3.

Table 3 Monthly Energy Generations (GWh)

Operation	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Existing	188.03	160.39	162.29	155.63	163.65	156.80	227.10	299.94	309.74	307.26	267.78	223
With e-flow	192.99	165.24	165.76	163.59	164.80	162.03	231.13	309.56	309.87	307.26	268.23	215.2*

* denote the power deficit than the existing power production.

4.4 Determination of Hydrologic Alteration by RVA analysis

Due to hydropower projects, the natural flow faces to the changes on the magnitude, frequency, duration, and timing of flow regime and their sediments. Alterations to the natural flow regime affect the structure and function of rivers and wetlands and contribute to loss of biodiversity worldwide (Bunn and Arthington 2002). [8] In this study, in order to quantify the extent of the changes, RVA analysis was used using the post dam flow (2011- 2018) and pre-dam one (1981-2009). This analysis was conducted based on 33 indicators within the five groups that categorized as magnitude, frequency, duration, timing and rate of changes [7]. The representative conditions for each group are as the followings;

Group 1: Magnitude of monthly water condition (m^3/sec)
Group 2: Magnitude (m^3/sec) and duration (Day) of annual extreme flow and base flow condition
Group 3: Timing of annual extreme flow (Julian date)
Group 4: Frequency (Number) and duration (Day) of high and low Pulse
Group 5: Rate and frequency of flow change (m^3/sec) [11].

Hydrological regimes can variable change according to operational rules and constraints in the reservoir operation system. In the study, the alteration analysis on post-dam flow from pre-dam one was conducted by the operations under existing policy and under e-flow restriction. The detailed analysis of alteration degree for 33 parameters within five groups is shown in Table 4 and mean alterations represented for each group are shown in Table 5.

Table 4 Percentage Alteration by RVA Analysis for IHA Parameters with Five Groups

Group 1	**% Alter**		**Group 2**	**% Alter**		**Group 3**	**% Alter**	
	existing	**with e-flow**		**existing**	**with e-flow**		**existing**	**with e-flow**
January	9.375	9.375	1-day minimum	100	67.05	Minimum date	100	39.58
February	100	67.05	3-day minimum	100	34.09	Maximum date	9.375	9.375
March	69.79	69.79	7-day minimum	67.05	100	**Group 4**	**% Alter**	
April	100	100	30-day minimum	67.05	100		**existing**	**with e-flow**
May	34.09	1.136	90-day minimum	100	100	Low pulse count	75.83	100
June	34.09	1.136	1-day maximum	39.58	9.375	Low pulse duration	100	100
July	1.136	34.09	3-day maximum	1.136	34.09	High pulse count	69.17	20.83
August	31.82	34.09	7-day maximum	34.09	67.05	High pulse duration	9.375	9.375
September	31.82	31.82	30-day maximum	34.09	34.09	**Group 5**	**% Alter**	
October	67.05	67.05	90-day maximum	100	67.05		**existing**	**with e-flow**
November	31.82	31.82	Number of zero flow days	0	0	Rise rate (m^3/s/d)	34.09	34.09
December	20.83	20.83	Base flow	64.77	34.09	Fall rate (m^3/s/d)	100	100
						Number of reversal	100	100

The parameters in IHA group (1) are important for the ecosystem influences such as habitat availability for aquatic organisms and water availability for terrestrial animals [11]. Monthly water condition can maintain the soil moisture for the plants. They can influence the water temperature, oxygen levels and photosynthesis in the water column.[11] Group (1) mean alteration leads to moderate levels by 54.19 % under existing operation and by 48.94 % under operation with e-flow constraint. It can reduce by 5.25 % under e-flow constraint than the existing case.

Under IHA parameters group (2), the alteration analysis was conducted by the variable flow conditions such as extreme low flow, high flow, flood and base flow. In duration of the extreme low flow condition, the riverine habitats face to the stress such as low oxygen, concentrated chemicals in aquatic environments. Duration of the stressful condition can also make the dehydration in animals, anaerobic stress and soil moisture stress in plants.[11] In the extreme low flow condition such as 1,3,7,30,90 day minimum flow, the operation with e-flow constraint can release the flow to resemble natural pattern more than the existing operation. Therefore, under the operation with e-flow constraints, the ecosystem influences of this flow condition can be nearly the same as the natural condition. But high flow and flood condition (1,3,7,30,90 day maximum flow) have more deviation from the natural condition. As an impact, the volume of nutrient cannot exchange between the river and floodplain if the loss of flood happens.[11] Due to the less frequent in high flow pulse in the post flow regime, the essential ecosystem process such as the waste disposal and aeration of spawning beds in channel sediments has the problem.[11] Number of zero flow days that is one of the extreme low flow conditions has the same alteration level and alteration in base flow decrease to some extent. Overall, group mean alteration indicates that operation with e-flow constraint can reduce the alteration level to 63.39% from 68.97 % under the existing operation.

The alteration levels of group (3) parameters such as date of minimum and maximum are significantly reduced by operation with e-flow constraint than existing case and it decreases the alteration from high level to low level. As a benefit, it can synchronize the life cycles of the organisms as similar to the natural condition.[11]

In IHA group (4), under e-flow constraint, the groups mean alteration remains nearly the same level with the existing case and it cannot significantly reduce. The levels are still on the moderate range in both operations.

In IHA group (5), alteration levels in each parameter are the same value for two operation rules and group mean alterations have the same as severe range by 83.99%.

A single index from overall of 33 indicators within five groups indicates that the alteration level can be reduced from 66.1 % to 60.38 % when considering the environmental flow constraints in the reservoir operation system compared to the existing operation policy. The result indicates that the operation with e-flow constraint can perform the closet natural flow pattern with decreased alteration level and it can maintain the ecosystem integrity than the existing condition.

Table 5 Comparison of Group Mean and Single Index for Hydrologic Alteration Degree

IHA Group	**% Alteration and IHA Class**			
	Existing Operation		**Operation with e-flow constraint**	
Group 1	54.19	M	48.94	M
Group 2	68.97	H	63.39	M
Group 3	71.02	H	28.76	L
Group 4	71.8	H	71.63	H
Group 5	83.99	H	83.99	H
Single Index for 33 IHA parameters	66.1	M	60.38	M

4.5 Summary Result for Two Reservoir Operation Systems

Table 6 summarises the results between the existing operation policy and the operation with e-flow constraint. In the existing operation system, the simulated energy is 2621.612 GWh annually. This operation leads to the moderate alteration in the natural flow regime and it defines as the base case to compare with another operation. Under the operation with e-flow restriction, the simulated energy is 2655.654 GWh annually and power production increase 1.3 % than the base case. The released flow regime has the moderate alteration and this operation can reduce the impact by 5.73 % compared to the base case. The result indicates that the latter operation can manage the water to provide the environmental flow while increasing the energy generation.

Table 6 Summary Results for Two Operation Systems

Operation System	**Simulated Energy (GWh)**	**Change Power Production (%)**	**Alteration (%)**	**IHA Class**	**Change Impact (%)**
Existing	2621.612	Base case	66.1	M	Base case
With e-flow constraint	2655.654	+ 1.3	60.38	M	-5.73

V. CONCLUSION

Under the existing operation policy, the released flow regime cannot maintain the minimum environmental flow requirement in some periods. This operation leads to the moderate alteration on the natural flow regime. The river channel, habitats and aquatic species could be negatively impacted due to the alteration in the natural hydrological regime. Minimizing the degree of flow regime alteration is the key to protect the ecosystem. The objective of environmental flows is not to reproduce a natural flow regime in whole, but rather to achieve a flow regime that maintains the essential processes required to support healthy river ecosystems. In order to maintain the river health, the flow regime should meet the minimum environmental flow requirement as the beginning level. In order to reduce the impact risk on the riverine ecosystem, the alteration level should be controlled by the improved reservoir operation rule. When the downstream control function rule for minimum environmental release is considered as the first priority in the operation system, the alteration level can be reduced to some extent than the existing case while increasing the power production. The water management system can be improved by the reservoir operation that provides the environmental flow to support the downstream riverine ecosystem, and still maximizes energy production.

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REFERENCES

[1] Acreman, M. & Dunbar, M. J. (2004): Defining environmental river flow requirements - a review. Hydrology & Earth System Sciences 8[5], 861-876.

[2] Cate Brown, Jackie King, Jessica Hughes and Vaqar Zakaria, Environmental Flows for Hydropower Projects. Guidance for the Private Sector in Emerging Markets, February 2018.

[3] Lucas E. Calvo Gobbetti (2017): Application of HEC-ResSim in the study of new water sources in the Panama Canal, Journal of Applied Water Engineering and Research, DOI: 10.1080/23249676.2017.1335575.

[4] Mukand S. Babel, Chien Nguyen Dinh, Md. Reaz Akter Mullick, Umamahesh V. Nanduri, Operation of a hydropower system considering the environmental flow requirements: A case study in La Nga river basin, Vietnam, Journal of Hydro-environment Research 6 (2012) 63-73.

[5] Mullick, M. R.A., Babel, M.S.& Perret, R., (2010). Flow characteristics and environmental flow requirements for the Teesta River, Bangladesh. In the Proceedings of International Conference on Environmental Aspects of Bangladesh. University of Kitakyushu, Japan, September 4, 159-162.

[6] Nam, K., Cham, M.R.., and Halili, P.R., 2015, Power Sector Development in Myanmar, ADB Economic Working Paper Series, No. 460, October, Manila.

[7] Richter, B.D., Baumgartner, J.V., Braun, D.p., Powell, J., 1998. A Spatial Assessment of Hydrologic Alteration within a River Network. Regulated River Research Management 14 (4), 329-340.

[8] Robert J.Rolls, Catherine Leigh and Fran Sheldon, Mechanistic Effects of Low-flow Hydrology on Riverine Ecosystem: Ecological Principle and Consequence of Alteration. Freshwater Science, 2012, 31(4):1163-1186.
[9] Smakhtin, V.U. and Anputhas, M.2006. An Assessment of Environmental Flow Requirements of Indian River Basins. International Water Management Institute, Colombo, Sri Lanka. 42 pages. (IWMI Research Report 107).
[10] Tharme, R.E., 2003. A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers. River Research and Applications 19, 397-441.
[11] The Nature Conservancy, 2007. Indicator of Hydrologic Alteration, Version 7.1 User’s Manual.
[12] T. Seyoum & S. Theobald, Modeling of Cascade Dams and Reservoir Operation for Hydropower Energy Generation, ICHE 2014.