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SWAT Analysis for Investigating River Discharge and Operation Curve on Kulekhani Reservoir

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Abstract

Discharge data for inflow to a reservoir is a major factor for the determination of the capacity of a reservoir, its operating policy. The SWAT model has been implemented in the Kulekhani watershed for the calibration and validation of the reservoir inflow data. First applicability of SWAT model is checked for Kulekhani watershed by calibration and validation of river discharge for period (1972 AD to 1975 AD) and (1976 AD to 1977 AD) respectively. In a motive to generate the monthly river flow in the Kulekhani area up to 2017 AD, further SWAT model is calibrated for period 1972 AD to 1977 AD and, by using the parameter values from this calibration period, data of river discharge is calculated from SWAT CUP for period 1978 AD to 2017 AD. Using the calculated discharge, the reservoir water levels for 5 hypothetical net water requirement scenarios for no spilling condition, maximum reservoir level at end of October months, and minimum possible drawdown at end of June month is calculated for period 1972 AD to 2017 AD, and extended up to 2025 AD by increasing sedimentation level. The reservoir level has been decreased to minimum level during the wet years period and the reservoir is also able to fill up to maximum capacity due to enough rainfall. But during the dry and average years, the reservoir will not be able to maintain its full capacity from bottom of minimum level. So, for dry and average years reservoir is not emptied to minimum level.

Keywords

Kulekhani-I, Reservoir, River Discharge, SWAT, Calibration, Validation, Operation curve

1. Introduction

The Soil and Water Assessment tool SWAT is an extension of GIS-based software (ARCSWAT or QSWAT) used in the area of hydrology, land management, agriculture[1]. It is useful for weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pondage and reservoir storage, crop growth and irrigation, groundwater flow, river routing, nutrient and pesticide loading and water transfer analysis[1]. In this study it is used for the determination of runoff from the Kulekhani watershed, assuming outlet at the point on the dam axis. When calibrating a physically-based model like SWAT, it is important to keep all model input parameters within a realistic uncertainty range, as no automatic procedure can substitute for actual physical knowledge of the watershed [2]. The choice of parameterization will affect the calibration result in the model.

Calibration, validation, sensitivity analysis and uncertainty analysis of SWAT models is performed through SWAT CUP. In SWAT CUP, model uncertainty and input uncertainty are major reasons to create calibration and validation errors [2]. In this study, SUFI-2 algorithm is used for calibration and validation in SWAT CUP. SUFI-2 algorithm is defined as the difference between simulated and observed variables. The goodness of fit can be quantified by the coefficient of determination (R-square), percentage bias (PBIAS), and Nash- Sutcliff model efficiency coefficient (NSE) between the observations and final best simulation. The best solution is the final parameter range that gives better values of these performance indicators. R-square describes the degree of collinearity between simulated and measured data. NSE is normalized statistics that determine the relative magnitude of residual variance compared to the measured data variance. NSE value indicates how well the plot of observed versus simulated data fits, making NSE value 1 a perfect match. The general performance rating of stream flow calibration indicates 0.75 to 1 NSE value as very good, 0.65 to 0.75 as good, 0.5 to 0.65 as satisfactory, and less than 0.5 as unsatisfactory values. PBIAS is another performance indicator, which measures the average tendency of the simulated data to be larger or smaller than observations. So, the less the PBIAS the better the calibration. The PBIAS value less than 10 percent is considered to be very good calibration results, 10 percent to 15 percent as good, 15 percent to 25 percent as satisfactory, greater than 25 percent as unsatisfactory results[3]. In this study SWAT is used for the determination of runoff from the Kulekhani watershed, assuming outlet at the point on the dam axis.

Kulekhani -I HES have been in operation since 1982 AD with a primary annual generation of 165 GWh[4].It has some special features in operation as it operated during peak hours, often for voltage improvement and system stability, and it starts operation during blackouts and energizes the main transmission line [4]. And it is operated based on the reservoir level and energy demand as directed by the Load Dispatch Center[4]. This demand-based operation may be helpful but this kind of utilization has raised the question of its sustainability [5]. Looking at the annual energy generation reports, the power plant has not been able to generate a designed amount of energy from 2000 AD to 2017 AD. The rainfall, river discharge along with current reservoir operation levels, energy generations are analyzed and the reservoir operation rule curve for conditions of no spilling, maximum reservoir level at end month of monsoon is studied in this research.

2. Literature Review

The performance of SWAT model is good for simulating river discharge in the Himalayan and tropical basins of Asia [6].It has been applied in the complex mountainous river basin of Budhigandaki to simulate rainfall runoff characteristics [7]. It was applied in IB River watershed in India to simulate the stream flow, which resulted good treaty between observed and simulated stream flow [8].It was applied to estimate the annual runoff and sediment of Duhok reservoir watershed due to lack of continuous field measurement of runoff and and sedimentation [9]. And, SWAT is feasible to use as flow and transport simulator for hydrological modeling and water quality in pre alpine Thur watershed[10].

The rule curve is represented as the reservoir elevations at different times which requires consideration of the limiting factors and storage allocation. The maximum and minimum elevation can be varied depending upon the inflow and demand conditions at different months according to net water requirement. In determining the reservoir operation curve for storage conservation there is interest in determining the lowest needed storage at each month, during the year such that water can be released with pre-determined reliability of supply. If the year is dry then the storage level at the beginning of the year should be high to reduce the possible effect of drought on demand and supply [11]. The Kulekhani plant has been designed by Nippon Koi. The rule curve for the Kulekhani operation at the designed phase is based on the energy situation of that time and the projected future scenario.

3. Objective

The objectives of the study are as follows:

- To analyze validity of SWAT application, and to calculate reservoir inflow using SWAT.
- To Calculate reservoir operation rule curve for conditions of no spilling, maximum reservoir level at end month of monsoon considering sedimentation level at working period for 5 hypothetical net water requirement conditions.

4. Data Study

Daily rainfall, temperature, and discharge data have been collected from the Department of Hydrology and Metrology (DHM). Thiessen polygon is prepared to choose the rainfall and temperature stations nearby the study area. According to this, the gauge stations of Markhu gau, Daman, Thankot, and Chisapani cover 47.87 percent, 41.51 percent, 10.37 percent, and 0.25 percent respectively. The Markhu gau and Daman are the most dominant stations that affect the inflow in the reservoir, consecutively followed by Thankot and Chisapani as impacting stations for rainfall on the Kulekhani watershed. The missing rainfall in the station's area was calculated by the weighted average missing precipitation method regarding Chisapani, Hetauda NFI, Makawanpur Gadhi, Markhu Gau, and Thankot stations. Daman is the only available temperature station within the Kulekhani watershed.

There is no available evaporation data for the Kulekhani watershed to simulate the river discharge, and it was determined by SWAT model using the Hargreaves method. Hargreaves method is chosen because there is only precipitation and temperature data available for the study area.

And for this study, monthly Energy generation from Kulekhani-I and total monthly energy generation in Nepal is refered from NEA annual reports. GCM data is refered from ICIMOD. The soil data is downloaded from the FAO-website, and the Land-use data is refered from the ICIMOD report. DEM of 30m resolution is used in the watershed delineation.

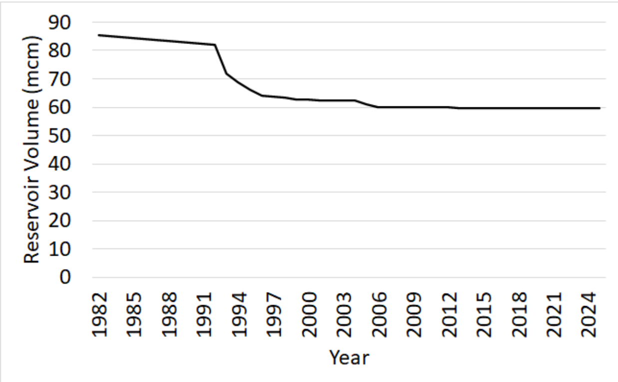


Figure 1: Reservoir capacity with time

The level for reservoir drawdown is dependent of the sedimentation level. Figure 1, is prepared from the reference of the data presented in the various literatures[12, 13, 14, 15]. To counter flooding disasters in the future, the Kulekhani Disaster prevention project has constructed a sloping intake for power plant, and a series of erosion control dams. The sediment flow in the flooding year 1993 AD was 4.8 MCM (6 percent of reservoir capacity) and after the disaster prevention project i.e. from 1996 AD to 2002 AD average annual flow of sand is 0.29 MCM which is a 94 percent reduction from flooding year [16]. The measured sedimentation data by NEA upto 2010 AD is extended linearly upto 2025 AD, so that minimum drawdown level could be estimated upto 2025 AD. The minimum water level specified in Figure 1 is used during the reservoir operation curve calculation.

In this study, the 25 percentile, 50 percentile, and 75 percentile value of rainfall from 1972 AD to 2018 AD is 1282.15 mm, 1559.63 mm, and 1802.83 mm respectively. In Figure 2, years with an annual rainfall below 25 percentile lines are dry, and years above the 75 percentile lines are wet years. The years that have

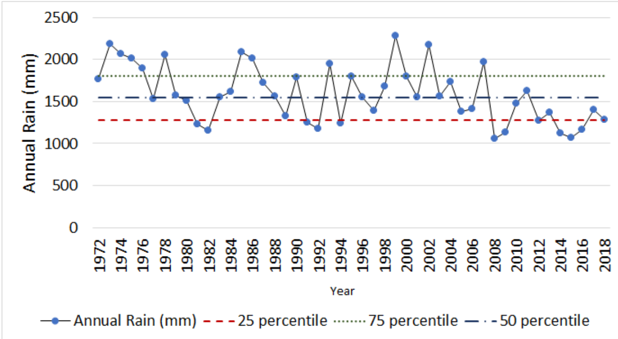


Figure 2: Annual rainfall showing 25 percentile, 50 percentile, and 75 percentile line to classify years in to dry, average, and wet years

rainfall values between 25 and 75 percentile lines are average years. There are no exact classification criteria to distinguish years as wet years, an average year, and a dry year[17]. For simplicity and ease of analysis, years have been classified to wet, average, and Dry years based on average rainfall for 1972 AD to 2018 AD. In the graph, most of the years before Kulekhani construction started are wet years with higher precipitation values. During the Kulekhani operation from 1983 AD to 2000 AD, there were more wet years and average years than dry years. And, from 2000 AD to 2017 AD, the only wet years are 2002 AD and 2007 AD. During this study, the monsoon, pre-monsoon, post-monsoon, and dry seasons have 75.91 %, 16.51 %, 3.57 %, and 4.06 % contribution in yearly rainfall respectively. As most of the rainfall occurs during the monsoon, it is a period for refilling in the Kulekhani reservoir.

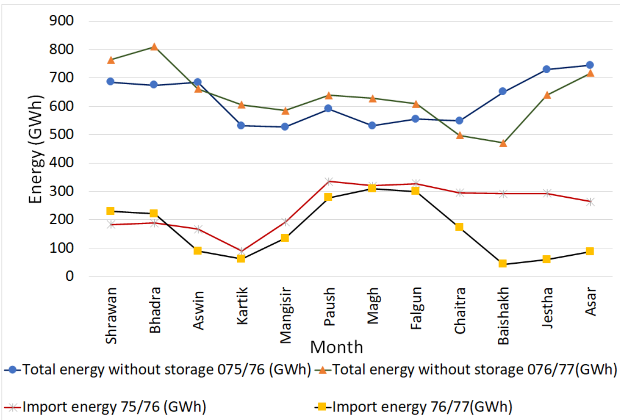


Figure 3: Monthly Energy Production in Nepal(without considering the contribution of the Kulekhani) and Monthly Imports[4]

When the generation is lower, there will be more insufficient energy to meet the demand of country, and more energy will be demanded from Kulekhani HES. A hypothetical condition of net water requirement condition based on total monthly energy generation without Kulekhani HES is assumed as condition 3, in section 4.3 with reference from the energy generation scenario in Figure 3. Assuming the imports of electricity are only governing factors for determining net water requirement to operate Kulekhani HES, two hypothetical conditions based on import at 2075/76 and 2076/77 are assumed on section 4.3 for condition 1 and 2 respectiveily, for calculation of reservoir operation curve from reference of Figure 3.

The newly completed projects, their monthly energy generation and installed capacity will increase available energy in the national grid. As the upper Tamakoshi HPS project is a daily peaking generation type, its monthly energy generation varies with river discharge. With the development of the Tamakoshi project, the national grid demand for electricity for the Kulekhani plant would be changed. Monthly water requirements are based on Tamakoshi river discharge data at station 647, for condition 4 in section 4.3.

A good mix among ROR, PROR, and storage projects within Nepal, is necessary for the balanced energy supply. When there is no availability of the energy from the storage projects or there is only ROR type of projects, the energy production will be directly proportional with river discharge. Narayan Prasad Chaulagain's thesis on 'Impacts of Climate Change on Water Resources of Nepal, the physical and Socioeconomic Dimensions' has presented all Nepal river discharge as sum of runoff data observed at 50 hydrological stations, and snow and glacier melt water. The snow and glacier melt water rate, calculated from study of Langtang area was used to generate total snow and glacier melt water[18]. The calculated discharge in literature [18] was used to calculate the net water requirement calculation condition 5, in section 4.3.

And for the river inlfow, SWAT is applied to calculated runoff from the Kulekhani watershed, assuming outlet at the point on the dam axis. There are 15 years of discharge data available for station 570 from 1963 AD to 1977 AD in DHM, but precipitation data was only available from 1972 AD. This data is used for calibration and validation of SWAT discharge results from 1972 AD to 1975 AD and 1976 AD to 1977 AD. And, the runoff from the watershed is determined using the precipitation and temperature data from DHM via the SWAT cup, by using calibrated parameters of the period 1972 AD to 1977 AD. SWAT weather data is generated through wgn parameter estimation tool. It has prepared the files in the required format to input on ARCSWAT weather data analysis [19]. During the watershed delineation, 27 sub-watersheds were generated. And during HRUs analysis, a 5 percent threshold for land use, slope, and soil type is assumed. There are altogether 220 HRUs in the watershed. HRU is the smallest spatial unit of the model. The standard HRU definition approach lumps all similar land uses, soils, and slopes within a subbasin based upon user-defined thresholds [20].

5. Results and Discussion

5.1 Calibration (1972 AD – 1975 AD) and Validation (1976 AD, 1977 AD)

The monthly mean inflow data obtained from DHM is used as observed data for the SWAT analysis, taking 1972 AD as the warm up period and 1973 AD, 1974 AD, 1975 AD as the calibration period. Sensitivity parameters are selected so that the models could be represented more physically as possible in SWAT Calibration. The parameters are selected based on modeling objective, soil, geology, hydrology, land-use, slope based on works of literature [21],[22],[23]. Initially, the model setup was calibrated with only one parameter CN2 and then a second iteration was conducted with the parameters shown in Table 1. Parameters are checked if these are in the acceptable limit as specified by Absolute_SWAT_Values.txt file. These parameters are modified as suggested by new_para.txt file generated after calibration, for each iteration. Before each iteration, review the suggested new parameters in the new_paras.txt file, and make a new iteration with new suggestions. The parameters were checked if those are within the acceptable limit, if not they were modified to an acceptable limit as suggested in Absolute_SWAT_Values.txt file. The final parameter fitted value in the SWAT simulation model and its range after 2000 simulations are as in Table 1. The better calibration results were found out while taking all 22 parameters to the last iteration during calibration. So, all the 22 parameters were calibrated to 4^{th} iteration.

The first letters R and V at the parameter symbol represent relative and variable calibration parameters method respectively, which defines how the parameter values are changed during the number of simulations.

S.N.	Parameter Symbol	Parameter Name	Fitted value	Min. Value	Max. Value
1	R_CN2.mgt	SCS curve number	0.02	-0.04	0.12
2	V_ALPHA_BF.gw	Baseflow alpha factor	0.47	0.21	0.63
3	V_GW_DELAY.gw	Ground water delay	46.28	0	328.23
4	V_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	252.95	0	1720.79
5	V_SURLAG.bsn	Surface runoff lag coefficient	11.13	0.05	20.69
6	R_SOL_Z(..).sol	Depth from soil surface to bottom of layer	-0.12	-0.13	0.04
7	R_SOL_AWC(..).sol	Available water capacity of soil layer	-0.05	-0.09	0.16
8	R_SOL_K(..).sol	Saturated hydraulic conductivity	-0.11	-0.13	0.06
9	R_SOL_BD(..).sol	Moist bulk density	0.23	0.05	0.3
10	V_GW_REVAP.gw	Ground water revap coefficient	0.09	0.02	0.12
11	V_REVAPMN.gw	Threshold depth of waterin shallow aquifer for revap to deep aquifer to occur	288.41	223.91	358.01
12	V_RCHRG_DP.gw	Deep aquifer percolation factor	0.60	0.24	0.71
13	R_HRU_SLP.hru	Average slope steepness	0.12	0.04	0.25
14	V_SLSUBBSN.hru	Average slope length	125.12	81.98	142.14
15	V_ESCO.bsn	Soil evaporation compensation factor	0.56	0.23	0.69
16	V_EPCO.bsn	Plant uptake compensation factor	1.19	0.75	1.37
17	V_CH_N2.rte	Manning's n value for main channel	0.013	0.01	0.09
18	V_CH_K2.rte	Effective hydraulic conductivity in main channel alluvium	13.94	10	122.5
19	V_CANMX.hru	Maximum canopy storage	3.60	0	46.83
20	R_OV_N.hru	Manning's n value for overland flow	0.08	0.031	0.11
21	V_ALPHA_BNK.rte	Baseflow alpha factor for bank storage	1.13	0.77	1.37
22	V_LAT_TTIME.hru	Lateral flow travel time	89.57	33.49	100.49

Table 1: Fitted values, minimum, and maximum values for SWAT parameters

And, min_value and max_value are the range parameter values during simulations. Global sensitivity analysis uses the regression system to identify the relative significance of the parameter values. The parameter file type extensions used in Table 1 are '.mgt', '.gw', '.bsn', '.sol', '.hru', '.rte'. In SWAT Cup '.mgt' file are management file which contains properties regarding the itemization of land and water management practices. '.gw' is a groundwater input file to represent the character of groundwater flow, aquifer flow, and return flow to the river. '.bsn' file is a basin input file that defines general watershed attributes. '.sol' file defines the physical properties for all layers of soil. '.hru' file defines a diversity of features within HRU which can be grouped into topographic, water flow, erosion, land cover, and depressional storage areas. '.rte' files are the main channel input file that defines summaries physical characteristics of the main channel which affect water flow and transport of sediment, nutrients, and pesticides. Global sensitivities are estimates of the average changes in the objective function resulting from each parameter, while all other parameters are changing. The parameters without measurable significance in calibration are neglected for further simulation. The significance of the parameters can be measured with t-stat and p-value estimation during SWAT parameter sensitivity analysis. T-stat is the coefficient of a parameter divided by its standard error. Larger in absolute values of t-stat of a parameter, larger is the sensitivity. When the p-value is 0.05, there is only a 5% chance that the results you are seeing would have come up in a random distribution. So, there is a 95% probability of being correct that the variable is having some effect. And the closer the p-stat value towards zero, the more sensitive is the parameter.The value of R square PBIAS, NSE value is found to be 0.94, 0.5%, and 0.93 respectively for calibration of period 1973 AD to 1975 AD after 2000 simulations (500 first simulations +500 second simulations + 1000 final simulations). The observed data validation shows that the best simulation has a good fit that the values of NS and PBIAS are 0.6 and 0.9% respectively. The graph of observed and best simulation along with the 95 percentage prediction uncertainty plot in Figure 4 , has represented no considerable variation between simulated and observed data. The simulated data seems to be reliable all-time, excepts at peak inflow and rapid variation of inflow discharges (i.e., seasonal variation of discharge of neighboring year).

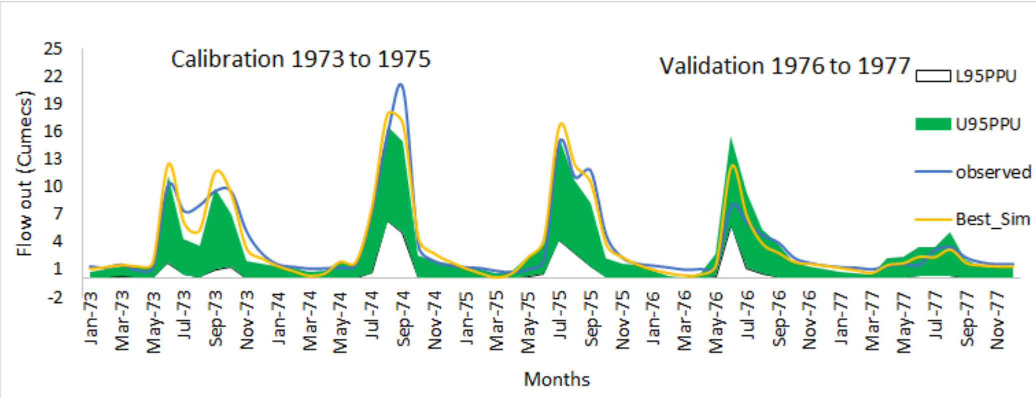


Figure 4: 95 PPU, observed and best simulation plot

5.2 Calibration (1972 AD to 1977 AD) and River Discharge Calculation

The runoff has been calculated from the SWAT model with the input of the precipitation, temperature data as input, and with the SWAT parameters. The SWAT parameters which have been used for calibration and validation for 1972 AD to 1975 AD and 1975 AD to 1976 AD are proved to be compatible in the Kulekhani watershed. The Kulekhani river discharge is again calibrated for the period 1972 AD to 1977 AD.The calibration results, NSE and PBIAS value as 0.94 and 0.5% after 2000 simulations (500 first simulations +500 second simulations + 1000 final simulations).

With the parameter from the final best fit value, further discharge calculation is conducted from 1978 AD to 2017 AD through 1000 simulations.The discharge values are calculated are on a monthly format. But, there is no monthly measured discharge from 1978 AD to 2017 AD. So, the calculated data cannot be directly validated with measured river discharge. And for the validation, simulated discharge is converted to yearly water volume. And yearly measured water volume is calculated by converting yearly energy to volume from generation data of Kulekhani. The overall efficiency of 85 %, average gross head 594.5m, avg. effective head 590.7 m, and average tailwater elevation of 916 masl, retrieved from the design report of the Kulekhani I hydropower plant[12]. Rated head, max head, and min head of Kulekhani-I as,550 m,605 m,518 m respectively. The rated and runaway speed for the Pelton turbine (type: VP-IR4N manufactured in 1979 AD by Fuji Electric Co. Ltd) is 600 rpm and 1140 rpm. Using this parameter, the volume of water used within a year has been calculated by the formula $V = Energy/(\eta\gamma H)$. The volume of water is calculated directly from the energy produced, which is the outcome after all types of losses have been counted including evaporation loss, seepage loss, hydro-mechanical head loss, etc. Then data validation was checked these two series of data using the NSE and PBIAS methods. The validation of these two data results in NSE and PBIAS values 0.7 and 8.67% respectively. This shows good simulation results and for the further discharge data calculation from 1978 AD to 2017 AD.

5.3 Initial Release for Rule Curve Calculation

The verified simulated data of monthly runoff is a major input for the calculation, to find out the reservoir operation pattern or rule curve. Along with runoff data, area elevation curve, net water requirement pattern for the different scenarios the new rule curve is intended to find out via using reservoir water balance equation. During model calculation, the net water requirement is estimated for the following hypothetical scenarios or conditions.

Condition 1: Monthly water requirements are based on Imports of electricity in the fiscal year 2075/76 BS when there is no contribution of Kulekhani storage. The numerical value of water requirement is taken as the total percentage of electricity import during a month of 2075/076 BS multiplied by the total volume of water inflow within a reservoir. The year 2075/76 BS is considered a business-as-usual year.

Condition 2: Monthly water requirements are based on Imports of electricity in the fiscal year 2076/77 BS. The numerical value of water requirement is taken as the total percentage of electricity import during a

Month		Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Sum
Inflow 2006/07		5.2	4.5	2.5	3.4	2.2	1.8	3.8	6.8	10.4	33.1	36.1	14.3	124.1
Condition 1	**Import % 2075/76**	4.8	8.9	11.1	11.0	10.6	10.0	9.9	9.4	7.6	6.3	6.0	4.4	100
	Release	5.9	11.1	13.8	13.6	13.1	12.4	12.3	11.7	9.4	7.8	7.5	5.4	124
Condition 2	**Import % 2076/77**	4.9	10.4	14.8	15.3	11.9	5.4	2.6	3.7	8.0	11.4	7.8	3.8	100
	Release	6.1	12.9	18.4	19.0	14.7	6.7	3.2	4.6	9.9	14.1	9.7	4.7	124
Condition 3	**Generation (TWh)**	203.3	168.2	137.2	123.3	129.9	157.1	203.8	232.3	229.5	228.7	228.4	222.6	2264.3
	% of (1/Gen)	7.3	8.9	10.9	12.1	11.5	9.5	7.3	6.4	6.5	6.5	6.5	6.7	100
	Release	9.1	11.0	13.5	15.0	14.2	11.8	9.1	8.0	8.1	8.1	8.1	8.3	124
Condition 4	**Tamakoshi dishcharge**	58.9	38.5	29.3	25.5	24.4	28.4	53.7	169.9	423.0	493.8	312.9	124.7	1783
	% of (1/Discharge)	7.3	11.2	14.7	16.9	17.6	15.1	8.0	2.5	1.0	0.9	1.4	3.4	100
	Release	9.1	13.9	18.2	21.0	21.8	18.8	9.9	3.1	1.3	1.1	1.7	4.3	124
Condition 5	**50 stations discharge**	6.6	4.4	4.2	3.7	3.6	3.8	5.4	14.2	36.9	43.2	34.3	14.0	174
	% of (1/Dischrge)	8.3	12.5	12.9	14.9	14.9	14.4	10.0	3.8	1.5	1.3	1.6	3.9	100
	Release	10.3	15.5	16.1	18.4	18.5	17.8	12.4	4.7	1.8	1.6	2.0	4.8	124

Table 2: Initial Release in the Calculation

month multiplied by the total volume of yearly water inflow within a reservoir. The year is considered as the year affected by Covid-19 (pandemic year).

Condition 3: Monthly water requirements are based on monthly energy generation without considering energy contribution from Kulekhani. The monthly generation taken here are average energy of fiscal year 2067/68 BS to 2076/77 BS. The net water requirement is determined by multiplying the total yearly inflow volume within the Kulekhani reservoir by percentage reciprocal of average energy generation.

Condition 4: The net water requirement is determined by multiplying the total yearly inflow volume in the Kulekhani reservoir by the percentage reciprocal of Tamakoshi discharge.

Condition 5: Monthly water requirement based on the monthly discharge of all rivers of Nepal: The net water requirement is determined by multiplying the total yearly inflow volume in the Kulekhani reservoir by the percentage reciprocal of all Nepal river discharges.

The release of water on different months and corresponding monthly energy generation gets different in each condition according to corresponding net water requirement as in Table 2, which will affect available storage and corresponding reservoir elevation. In Table 2, the inflow of water from 2006/November to 2007/October is taken as the sample data for the calculation of net water requirement of all five conditions. As stated in different conditions, the initial release calculation has been shown in Table 2.

5.4 Reservoir Operating Policy

Due to lack of river discharge data of the river, it is calculated through SWAT model from 1978 to 2017 AD. But the sedimentation measurement data has been continuously measured by NEA through bathymetric survey. Hence the river discharge data simulated from SWAT and sedimentation from NEA has been used in this study for calculation of reservoir operation curve. While determining the rule curve for storage conservation lowest needed storage at each time during the year is of interest such that water can be released with pre-determined reliability of supply. The standard operating policy of reservoir is based on water balance equation;

$S_{t+1} = S_t + Q_t - R_t$

Where,

S_{t+1} = End of month storage

S_t = Beginning of month storage

Q_t = Inflow during month

R_t = Release during the month

Storage at end of the month is equal to the sum of storage at the beginning of the month storage and inflow which is deducted by the release of water from the reservoir during the month. The calculation of water balance equations was checked for the spill of water and storage at the end of the month of monsoon

(at end of October).
$Spill = (S_t + Q_t - R_t) - K$
when, $(S_t + Q_t - R_t) > K = 0$ else
When storage volume goes beyond the limits, it is adjusted by adjusting release. Increase and decrease of release at previous months are conducted proportionately with net water requirements to maintain upper and lower limits of storage. The spill of water is reduced to zero by increasing release in the previous months. Maximum elevation at end of October is achieved by decreasing release at the previous months, considering monsoon at the refilling period for the reservoir. The reservoir could be operated for maximum 24 hours, can be filled up to 1530 masl, and can be emptied to minimum operation level only. The value of maximum reservoir level remains the same for all operating years unless the height of the dam is increased but the storage capacity gets decreased due to sedimentation. The reservoir capacity with time has been presented in Figure 1. The minimum reservoir operation level and its corresponding useful volume during the study period are as follows.
= 1475.6 masl, 73.3 MCM volume up to 1993 AD
= 1489.7 masl, 62.27 MCM volume up to 2004 AD
= 1493.0 masl, 59.53 MCM volume up to 2025 AD

During the storage balance equation, evaporation loss and seepage loss from the reservoir are not considered. The spill volume and storage at end of the monsoon have been checked for each year. If storage at end of the month is 1529 masl to 1530 masl, and no-spill at a year, the calculation objective would be satisfied. If the calculation objective is not satisfied, the release of a month will be changed according to net water requirement conditions. Then again storage volume at end of months is calculated by the storage balance equation and checked for the condition of no spilling and maximum storage at end of the monsoon. This cycle is repeated until the condition is satisfied. And the final release and corresponding reservoir elevation are calculated, and corresponding energy generation through reservoir release is calculated via the formula:
$E = P * t$
$= \eta * \gamma * Q * H * t$
Where, E = Energy, P = Power, t = Time of operation, η = Overall efficiency = 0.85[12].γ = specific weight of water,
Q = inflow to turbine
= 12.1 m3/S (capacity release when both turbine units are operational)[4]
H = Head

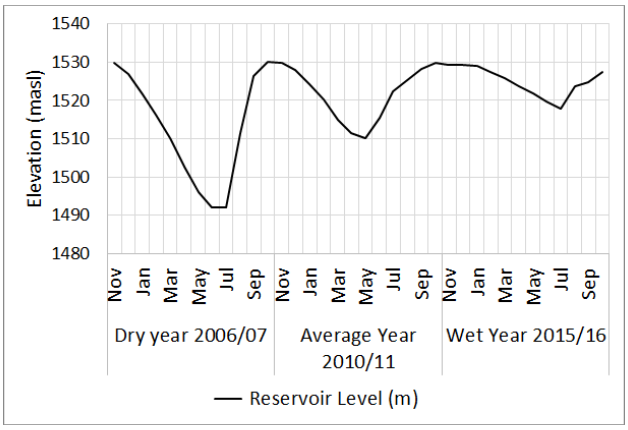
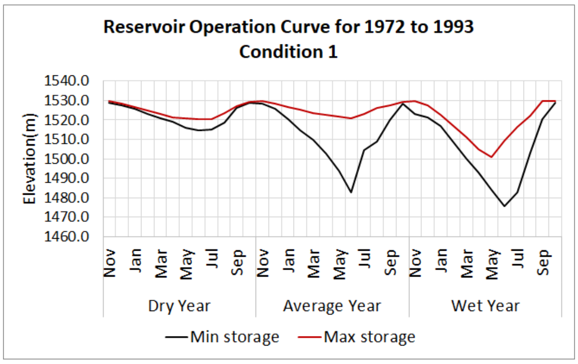


Figure 5: Reservoir Elevation Chart for Net after Requirement Condition 1

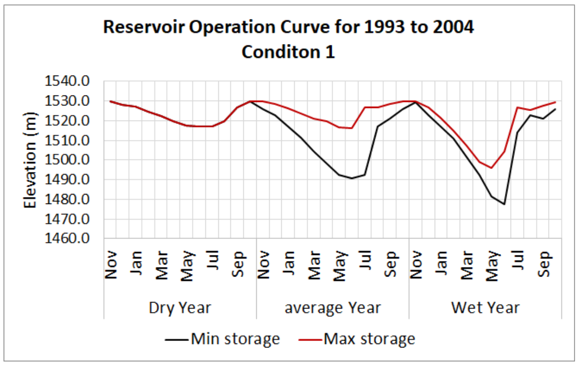
In Figure 5, the reservoir level has been decreased to a minimum level at the wet years period, and the reservoir is also able to fill up to maximum capacity, but the reservoir is not lowered to minimum possible drawdown in average, and dry years. If the reservoir level is lowered to minimum during the dry and average years, the reservoir will not be able to maintain its full capacity due lack of inflow.Hence to obtain the full reservoir capacity reservoirs levels are not emptied to a minimum possible level and the release during the monsoon also decreased to fill up the reservoir, as shown in Figure 5. The year 2007 AD , 2011 AD , and 2016 AD is a representation of wet year, average year, and dry year respectively, shown in Figure 2.

Minimum and maximum water level for wet years, average years, and dry years for different months is calculated for 1972 AD to 1993 AD, 1993 AD to 2004 AD, and 2004 AD to 2017 AD. These three periods are considered based on the minimum possible drawdown level for sedimentation. Taking the minimum possible operating level corresponding to projected sedimentation at 2025 AD, the rule curve has been extended from 2004 AD to 2025 AD.

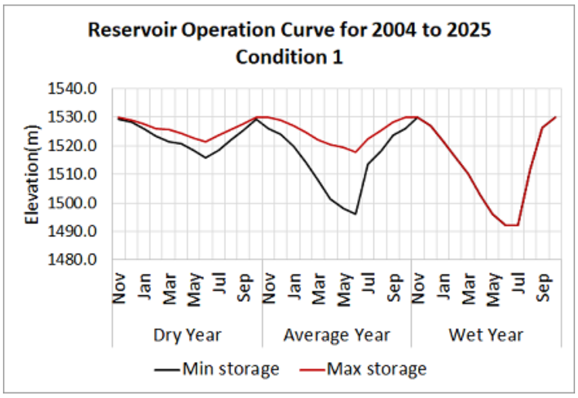
The gap between maximum and minimum elevation line is a possible reservoir level for reservoir operation. The gap is dependent on the inflow volume and net water requirement for the reservoir. Dry years has lesser gaps and gap increases for the average and wet year respectively. This is because the inflow variation, and quantity of inflow is less in dry years and inflow variation increases consecutively for average and wet years. Even minimum operating level is 1473 masl, and 1483 masl from 1972 AD to 1993



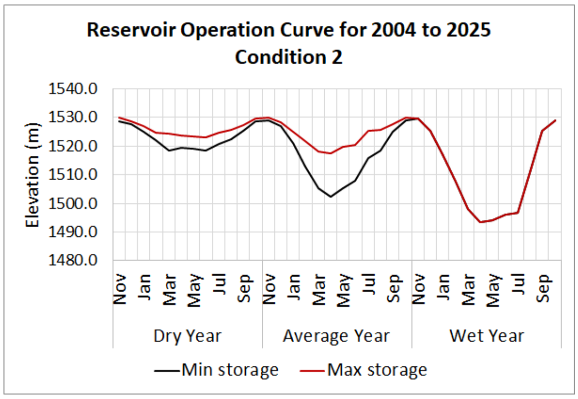
(a)



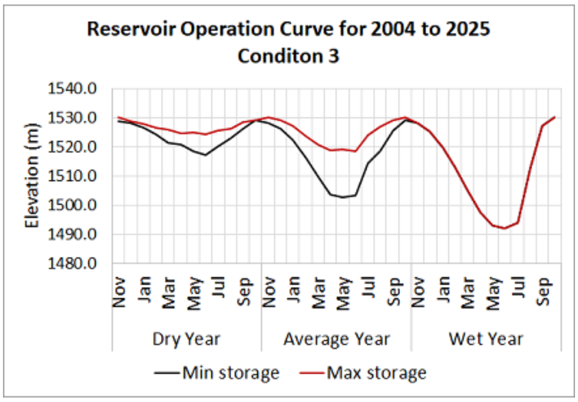
(b)



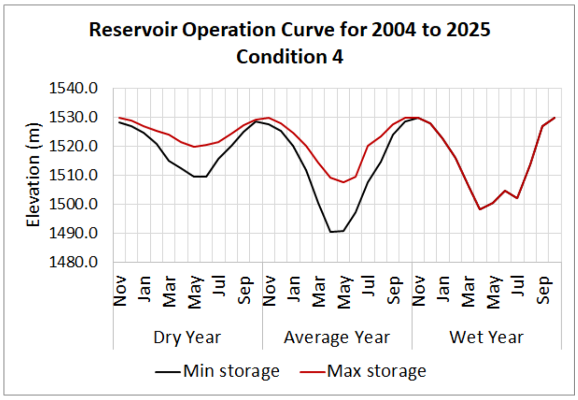
(c)



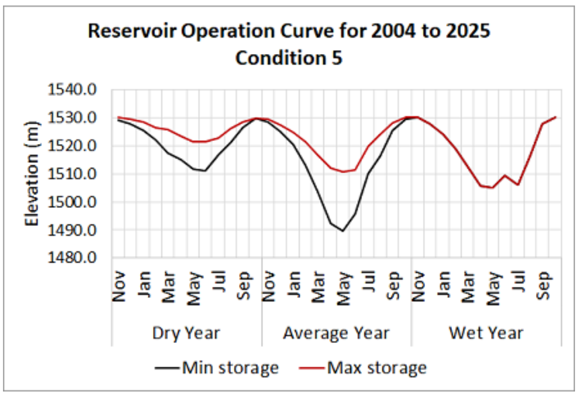
(d)



(e)



(f)



(g)

Figure 6: Reservoir Operation Curve up to 2025 AD for condition 1, 2, 3, 4, and 5 Respectively

AD, and 1993 AD to 2004 AD, it is not necessary to lowered up to a minimum point during operation for the generation of electricity as shown in Figure 6. Reservoir operation curve for 1972 AD to 1993 AD and 1993 AD to 2004 AD in Figure 6 is calculated for condition 1 only. There is only one dry year within the period 1993 AD to 2004 AD, which is 1994 AD. So there is only one line specifying both maximum and minimum operating levels. Reservoir operation curve usable up to 2025 AD for conditions 1, 2, 3, 4, and 5 are shown in Figure 6.

The reservoir is used upto a minimum in June and filled up after June. The gap between the min and max value is greater at June month which slowly decreased toward October months. The reservoir level needs to be operated to a minimum level when most of the rainfall occurs in the monsoon period so that the monsoon will again fill up the reservoir. But the reservoir is not necessary to operate to a minimum possible level when the net water requirement is fulfilled by the reservoir inflow. And, when the reservoir inflow balances the net water requirement the reservoir water level remains the same level. Since there is only one the wet year 2007 AD, within the period 2004 AD to 2017 AD, the upper and lower reservoir curve is the same and there is no gap.

5.5 Comparison of Calculated Reservoir Level and Real Minimum and Maximum Elevations

Table 3, is the representation of calculated data for the different years based on different net water requirement conditions, and real measurement records. The real measurement records for 2010 AD to 2017 AD are obtained from NEA. The data are compared in terms of minimum reservoir level, maximum reservoir level and annual energy generation. The reservoir operation curve set maximum reservoir level at end of October month so that the reservoir could have full potential of operation for next year. But the reservoir level was not maintained to maximum level in the real measurement records.

In Table 3, the real record of minimum and maximum values of reservoir level are less than that of calculated data for different conditions. As all 5 hypothetical conditions are based on simulated river discharge calculated by the SWAT model, so annual energy generation may not be similar. The sum of eight years of energy production from 2010 AD to 2017 AD in real record is 720.1 GWh, whereas for 5 different conditions, it is in the range of 685.61 GWh to 692.3 GWh. The Table 3 shows that for a similar amount of energy production, the reservoir drawdown level in June is higher than real condition. This shows that the Kulekhani reservoir has not been operated based on any of these conditions but operated on LDC command. And LDC operates Kulekhani reservoir for purpose of peak energy supply, voltage improvement, the black start of the system, etc.

6. Limitations

The first limitation on SWAT model is lack of measured temperature, humidity, solar radiation, and wind speed data to generate WGN parameters. The unavailable of data are derived from the neighboring stations of Kathmandu. Again, river discharge of Kulekhani river is not measured since 1982 AD, the reservoir operation curve are calculated based on the simulated river discharge from the SWAT CUP. And reservoir evaporation loss, seepage loss is not considered to calculate reservoir operation curve. The calculated reservoir operation curves for 5 different conditions are calculated by reservoir standard operation policy on excel environment, the use of more powerful calculation tools like MATLAB, for the reservoir operation optimization may have resulted better than this solution.

7. Conclusion

SWAT is used for the determination of reservoir inflow to the reservoir. As the value of NSE and PBIAS value for observed and simulated discharge for calibration and validation period, is within a good range, the SWAT model is applicable for the Kulekhani watershed. Then SWAT has been used to calculate the Kulekhani river discharge from 1978 AD to 2017 AD.

The 5 different net water requirement conditions discussed in this study have presented that the reservoir will only be able to drawdown to minimum level during wet years, but not on dry and average rainfall years as shown in Figure 6. Again, the expected amount of energy has been produced during wet years but failed to produce in the dry and average years. There are only two wet years in period 2000 AD to 2017 AD, they are 2002 AD and 2007 AD.

Condition	**Real measurement**			**N% is import 2075/76 based (Condition_1)**			**N% is import 2076/77 based (Condition_2)**		
Year	June	October	Energy	June	October	Energy	June	October	Energy
2010	1492.80	1521.20	86.70	1512.40	1529.80	100.50	1514.60	1530.00	90.90
2011	1490.80	1530.20	115.50	1515.60	1529.80	134.00	1507.50	1529.90	140.50
2012	1497.20	1530.30	111.60	1515.70	1529.80	89.10	1518.90	1530.00	91.30
2013	1497.50	1530.30	99.60	1516.10	1529.80	91.50	1516.70	1530.00	88.40
2014	1508.60	1530.30	79.90	1517.90	1529.60	60.00	1521.70	1530.00	62.40
2015	1508.30	1526.10	85.50	1521.10	1529.40	50.70	1524.30	1529.90	55.30
2016	1509.80	1522.80	73.40	1517.90	1529.40	62.30	1520.30	1530.00	57.00
2017	1503.70	1524.40	67.80	1517.80	1529.40	104.10	1518.30	1530.00	104.20
	Sum		720.10	Sum		692.30	Sum		690.10
Condition	**N% is total energy generation without KL based (Condition_3)**			**N% isTamakoshi discharged based (Condition_4)**			**N% is 50 stations discharge based (Condition_5)**		
Year	June	October	Energy	June	October	Energy	June	October	Energy
2010	1513.10	1529.70	91.00	1504.90	1530.00	90.40	1505.10	1529.90	90.40
2011	1510.50	1529.70	140.50	1492.80	1530.00	138.30	1494.90	1529.90	138.50
2012	1517.80	1529.80	91.50	1511.40	1530.00	90.90	1511.20	1529.90	90.90
2013	1516.30	1529.70	88.50	1508.30	1530.00	87.90	1508.80	1529.90	87.90
2014	1520.80	1530.00	64.80	1517.90	1530.00	62.20	1517.50	1530.00	62.60
2015	1524.10	1530.00	54.40	1521.00	1530.00	55.20	1521.20	1530.00	54.70
2016	1518.60	1529.10	57.20	1515.00	1529.90	57.30	1515.30	1529.90	57.00
2017	1518.40	1529.10	104.10	1509.50	1529.80	103.30	1510.90	1529.90	103.40
	Sum		691.99	Sum		685.41	Sum		685.61

Table 3: Comparison of Minimum and Maximum Reservoir Levels for 5 Net Water Requirement Conditions

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