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Simulation of Trade-Off among Planned Reservoir Projects and Inter-Basin Transfer Project: A Case Study of Sunkoshi River in Koshi Basin, Nepal

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Abstract

The Sun Koshi River is a major tributary of the Koshi River Basin in Nepal. There are a number of reservoir projects and inter-basin transfer projects planned for hydropower generation, irrigation, and water supply to the Terai Region of Nepal. These include the Sunkoshi Marin Diversion Multipurpose Project (SMDMP) which will divert the part of Sunkoshi river flow to the Bagmati river to irrigate the Terai's cultivable land. There are a few reservoir projects that are also planned in the River mainly with the objective of hydropower generation, which includes the two reservoir projects Sunkoshi III and Sunkoshi II. These projects are found to be studied and planned independently and in isolation without even considering the relationship (tradeoff) of one project with the others. This study endeavors to develop a simulation model considering the inter-relationships of all these three projects in the River Basin. The HEC-ResSim software is used for the simulation of the reservoir operations and diversion of water to meet the irrigation water requirements and to generate the maximum hydroelectricity from the projects. The developed simulation model was used to assess the tradeoff of benefits, in terms of energy generation and irrigation water supply, under different scenarios of project development. The results show that simulating and planning the whole system (three projects together) will yield a higher benefit in terms of energy generation while meeting the irrigation requirements than planning the three projects in isolation.

Keywords

Cascade Reservoir, Inter-Basin Transfer, HEC-ResSim, Reservoir Operation

1. Introduction

Water, being a crucial natural resource to support life, has got many other functional uses of hydroelectric generation, irrigation, recreation, etc [1]. The scope and the dimensions of the use of water have been increasing with time which reflects the dynamic consumption behavior. This dynamic nature has added complexity in sharing the benefit of water among all the stakeholders rationally [2]. By far, Integrated Water Resource Management (IWRM) techniques have been proven the most scientific and holistic approach to water management [3].

A fair amount of annual average rainfall with a huge elevation difference of terrain available in Nepal, allows it to produce an immense amount of hydroelectricity. Nepal has a gross potentiality of 83,500 MW of hydroelectricity generation of which 42,000 MW is technically and economically viable [4]. But, the spatial and temporal variability in rainfall and other geological conditions add some sort of uncertainties and dilemmas in decision making. Different studies have been conducted to identify the potential projects to optimally distribute the available resource. Generally, these studies need to be conducted on a basin-scale keeping in mind that the water and land resources are interrelated and form a unit[5]. When projects are studied, designed, and optimized in isolation, there will be conflicts in the operation of the projects in the river basin and the maximum benefits cannot be achieved. So, project studies and planning should be made in the scale of the basin, considering the trade-off and relationships of one project with the others to achieve the maximum benefits from the basin as a whole rather than focusing on a single project.

Simulation of the operation and relationships of projects at a basin-scale can help make the use of the water resources available in the basin while fulfilling all technical, economical, social and environmental, and other requirements (constraints) in the basin. A simulation is a modeling approach for simulating the behavior of a system on a computer, with all of the system's properties mainly represented by a mathematical or algebraic description [6]. Cascade reservoirs modeling and operation of a multipurpose function, which includes river flow modeling, reservoir storage, and water allocation through hydropower plants and other outlet groups, is more difficult [7].

HEC-ResSim was created to assist engineers and planners in conducting water resources studies in anticipating reservoir behavior and to assist reservoir operators in planning real-time releases during routine and emergency operations [8]. Simulations have been used for many years by different researchers to perform reservoir operations (e.g. [9, 10, 11]). The model mimics the actual decision-making process that reservoir operators must employ to meet operating criteria for electricity generation, flood management, and environmental release using an original rule-based methodology [7]. The HEC-ResSim model represents reservoir operating goals and constraints assigned with an original system of rule-based logic that has been specifically developed to represent the decision-making process of reservoir operation [8]. This study uses the HEC-ResSim reservoir simulation model as a tool for planning the reservoir operation of two cascade reservoirs and an inter-basin transfer project in the Sunkoshi river basin.

Reliability can be defined as the probability of a system being in a satisfactory condition. In other words, the complementary to the probability of failure or opposite of risk. Since both, the reliability and risk do not describe the severity and likely consequence of a failure of the system, other criteria such as resiliency and vulnerability have to be defined [12]. Resiliency describes the system's ability to bounce back or recover from the failure once it occurs. Prolonged failure events might have a severe impact on a project, so it is recommended to have a quick recovery from the failure as it occurs. The likely magnitude of failure, if one occurs is described by the vulnerability criteria. Sometimes, efforts to increase efficiency and reliability, increase the system's vulnerability to a costly failure [12]. In most cases, there exist a tradeoff among expected benefits, reliability, resiliency, and vulnerability. Using these three criteria can be an effective tool to describe how often, how long and how severe a failure might occur in a system.

2. Description of The Study Area

The Saptakoshi River Basin is located in eastern Nepal which has its origination from Tibet, China. The Sunkoshi River is the main tributary of the Saptakoshi river originating from the southern foot of the Himalayas. The headwaters of Sunkoshi originate from an elevation of about 8000 m.a.s.l. This paper deals with the two proposed storage hydropower projects Sunkoshi III and Sunkoshi II lying in its reach and one inter-basin transfer project Sunkoshi Marin Diversion Multi-Purpose Project (SMDMP) diverting water from the Sunkoshi II (Sunk III) pool. The dam site of the Sunkoshi III hydroelectric project is located downstream of 1.5 km of a confluence of Chauri Khola River and Sunkoshi River. The latitude, longitude, and altitude of the Sunk III HPP dam site are 27° 29' 50.5" N, 85° 48' 14.3" E, and 568m respectively. The full supply level of the reservoir is 700 m.a.s.l, the total installed capacity is 683 MW. The main purpose of this project is hydropower generation. The purposed Sunkoshi II (Sunk II) Hydroelectric station project is located in the Sindhuli and Ramechhap districts of Nepal. The latitude, longitude, and altitude of Sunkoshi II dam sites 27°14'53"N, 86°09'13"E, and 421 m.a.s.l . The normal storage level of the reservoir is 535 m.a.s.l, and the installed capacity is 978 MW. This project will serve to divert the required amount of irrigation water to SMDMP and produce hydroelectricity of excess discharge. The headworks site of SMDMP is located at Khurkot Village of Majhawa VDC (Sindhuli District) and the powerhouse site in Bhadrakali VDC (Sindhuli District). Geographically, their locations are between latitudes 27° 20' 38.64476" N and 27° 15' 31.5237" N and longitudes 85° 59' 03.90287" E and 85° 52' 29.99232" E.

The spatial and temporal variability of the precipitation can be seen with the season and the altitude variation in the study area. The land above the elevation of 4000 m.a.s.l is all covered with snow. The annual average precipitation of the high-altitude area at Mt. Himalaya

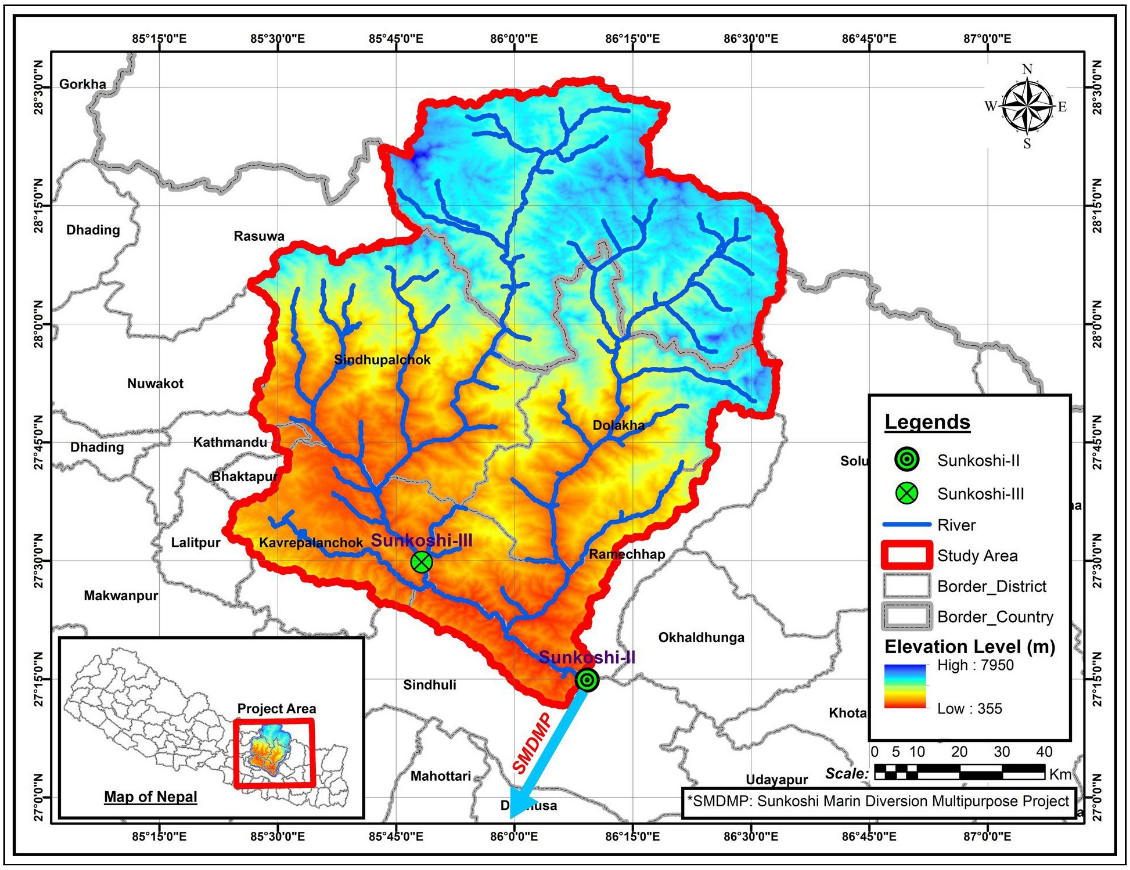

Figure 1: Location Map of Study Area

is about 1000 mm. The precipitation at SunKoshi River where the project locates is mainly seasonal with a small amount of snowmelt water. The land below the elevation of 4000 m.a.s.l is mainly forest and farming land. In dam sites, the annual average temperature is 25°C, the extreme highest temperature is 37.2°C, and the extreme lowest temperature is 7.6°.

3. Materials and Methods

3.1 Approaches of HEC-ResSim Model and Data

The simulation model demands intensive input data for reservoir simulation. These data include hydrological time series data, evaporation and other losses data, physical and operational data of dams and reservoirs, etc. This model is set up using monthly hydrological data so the routing parameters are excluded since they have little or no impact on flow data. The hydrological data were obtained from the Department of Hydrology and Meteorology (DHM) for the period of the year 1968 to 2014 of stations no 630 and 652 which lie near the proposed dam sites. The filling of missing hydrological data has been done using regression analysis. The HEC-ResSim simulation software has three modules which are the watershed setup, the reservoir network, and the simulation [8]. In the watershed setup module, schematic representations of the physical components of the project are drawn. The river reaches, junctions, and reservoirs are drawn and their properties are assigned in the network module. In the network module, the program demands all types of input feature data that the program needs to run the simulation. Finally, in the simulation module, the model is run for the desired period with a required number of alternatives. After assigning all the input parameters, the model is calibrated and the best alternative is selected for the reservoir operation.

3.2 Reservoir Operation Rules

The main objective of the simulation model is to operate the two reservoirs and the inter-basin diversion project to first generate the maximum average annual dry energy and total annual energy while meeting the irrigation and minimum downstream requirements and other physical and operational constraints. A coordinated operation rule is implemented in order to regulate the discharge from the reservoir which helps in generating maximum dry energy and total energy with acceptable performance indicators. Simulations are undertaken with different operation policies (several trials of buffer levels) and the operation policy that achieves the set objective is selected. A buffer level is the predefined level of elevation of water in the pool to be maintained at a given period (month) by releasing discharge up to its full capacity if the elevation at that time lies above it and cut off the release if it lies below.

3.3 Performance Evaluation

The results of the simulation are evaluated using certain performance indicators. Apart from the energy generation objectives, this study has used three such indicators, namely reliability, vulnerability, and resilience. Reliability can be defined as the number of data in a satisfactory state divided by the total number of data. Assuming satisfactory values in the time series X_t containing n values are those equal to or greater than some threshold X^T, then [13]

$$Reliability[X] = \frac{No.of time periods t such that X_t \geq X^T}{n}$$

Vulnerability [V] is a measure of the extent of the differences between the threshold value and the unsatisfactory values is calculated as[13]:

$$Vulnerability[X] = \frac{p}{q}$$

where,

p = [sum of positive values of $(X^T - X_t)$]

q = [number of times an unsatisfactory values occurred]

Resilience is the probability of having a satisfactory value in time period t + 1, given an unsatisfactory value in any time period t and can be calculated as[13]:

$$Resilience[X] = \frac{x}{y}$$

where,

x = [number of times a satisfactory value follows an unsatisfactory value]

y = [number of times an unsatisfactory value occurred]

3.4 Simulation Schemes

Three schemes are considered in this paper. Simulation of the two reservoir projects, Sunkoshi III and Sunkoshi II, and one diversion project, Sunkoshi Marin Diversion Multipurpose Project (SMDMP) in the Sun Koshi river is simulated for three schemes in this paper:

Scheme 1: Two reservoir projects are mainly operated for hydro-energy generation aiming to maximize dry energy (Dec-May) and Sunkoshi Marin Diversion Multipurpose Project (SMDMP) is operated to divert the constant design flow of 67 m^3/s.

Scheme 2: Two reservoir projects are mainly operated for hydro-energy generation aiming to maximize dry energy (Dec-May) and the Sunkoshi Marin Diversion Multipurpose Project (SMDMP) is only used to meet the discharge deficit, which is calculated after subtracting the flow contributed by the Bagmati River during the dry season. During the rest phase, or wet season, the steady discharge of 67 m^3/s will be diverted (Jun-Nov).

Scheme 3: Two reservoir projects are mainly operated for hydro-energy generation aiming to maximize dry energy (Dec-May) and Sunkoshi Marin Diversion Multipurpose Project (SMDMP) is excluded to assess the trade-off between irrigation and hydropower.

4. Results and Discussion

Scheme 1 findings: In six alternative simulations conducted using six different operation rule (OR), as shown in figure 2,

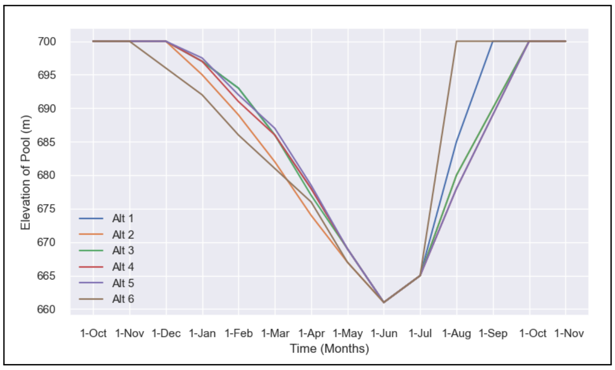

Figure 2: Alternative operation rule curves used in the Sunkoshi III

to maximize the hydro energy generation, Alternative 1 reservoir operation policy is selected to operate the reservoir Sunkoshi III based on the mean annual energy generation capacity, dry energy capacity, and

Table 1: Comparison of Three Schemes' Performances

	Project		Sunk III	Sunk II	SMDMP	Total
Scheme 1	Firm Power (MW)		127.0	104.0	28.3	
	Energy (GWh)	Total	2436.7	2900.2	248.1	5585.0
		Dry	681.2	600.8	123.7	1405.7
	PI for Dry Period Firm Power (%)	Reliability	94.8	95.6	100.0	
		Vulnerability	3.0	8.8	-	
		Resilience	85.7	83.3	-	
Scheme 2	Firm Power (MW)		127.0	121.0	17.0	
	Energy (GWh)	Total	2436.7	2956.6	219.4	5612.6
		Dry	681.2	657.1	95.0	1433.3
	PI for Dry Period Firm Power (%)	Reliability	94.8	94.8	91.6	
		Vulnerability	3.0	5.7	-	
		Resilience	85.7	71.4	-	
Scheme 3	Firm Power (MW)		127.0	161.0	-	
	Energy (GWh)	Total	2436.7	3342.9	-	5779.6
		Dry	681.2	843.2	-	1524.4
	PI for Dry Period Firm Power (%)	Reliability	94.8	95.2	-	
		Vulnerability	3.0	6.2	-	
		Resilience	85.7	84.6	-	

Performance Indicators (PI) criteria. If the reservoir Sunkoshi III operates in this operation policy, it will generate average annual energy of 2436.7 GWh/year of which dry energy will be contributing to 681.2 GWh/year of energy. The plant will be able to generate 127 MW firm power with 95% reliability during the dry season (Dec-May).

Similarly, in six alternative simulations using six different reservoir operation rules for Sunkoshi II, as shown in Figure 3,

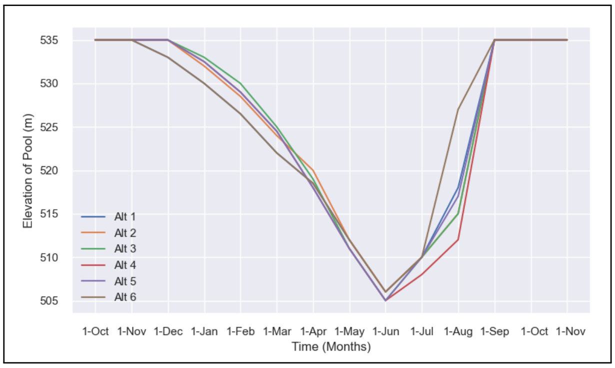

Figure 3: Alternative operation rule curves used in the Sunkoshi II

the Alternative 5 operation policy generated the maximum energy within the acceptable performance evaluation criteria. It generates an average annual energy of 2900.2 GWh/year of which 600.8 GWh/year comes from the dry period. It provides 104 MW of dry period firm power with 95% of power reliability.

While extracting a constant flow of 67 m^3/s from the reservoir Sunkoshi II in Scheme 1, SMDMP generates the total annual energy of 248.1 GWh/year running as a run of river powerplant and produces 28.3 MW of firm power with cent percent reliability.

Thus, the system generates the average annual energy 5585.0 GWh/year of total energy which includes 1405.7 GWh/year of dry energy.

The output plot of the HEC-ResSim simulation with the reservoir operation rule curve of Alternative 1 of reservoir Sunkoshi III is shown in Figure 4. The top figure shows the reservoir is strictly following the buffer level while drawing the water from the reservoir during the dry period. However, in the wet season due to randomness in the inflow pattern, a path cannot be governed easily. The inflow-outflow graph of the same figure indicates there is an appreciable rise in the dry flow due to controlled release from reservoir Sunkoshi III. The regulated outflow is governed by the constraints of ensuring diversion release of 67 m^3/s at the SMDMP inlet and the minimum environmental release. So, green line indicates outflow that satisfies above criterias.

The Alternative 1 rule curve is fixed as a reservoir operation rule for Sunkoshi III and six alternatives of reservoir operation policies were simulated for Sunkoshi II. Similarly, the Elevation and Inflow-Outflow curves for the Sunkoshi II reservoir for the operation rule curve of Alternative 5 is shown in Figure 5. Here, the first priority of regulated outflow is to meet the SMDMP release in coordination with Sunkoshi III reservoir outflow. An excess of water will flow from powerplant of Sunkoshi II following the operation rule curve.

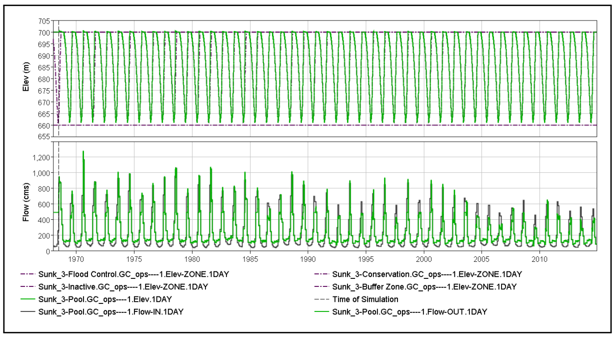

Figure 4: Reservoir Elevation and Inflow- Ouflow curves generated by reservoir operation policy of Alternative 1 in Sunkoshi III of Scheme 1

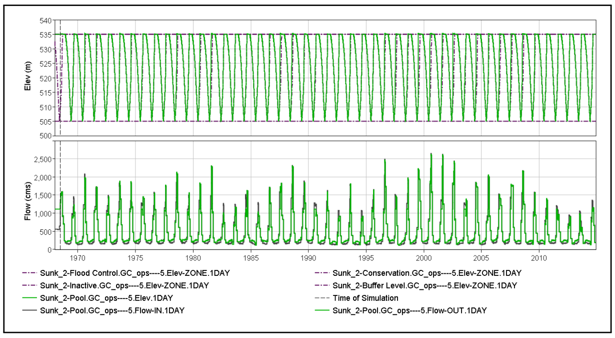

Figure 5: Reservoir Elevation and Inflow- Outflow curves generated by reservoir operation policy of Alternative 5 in Sunkoshi II of Scheme 1

Scheme 2 findings: Six alternatives' simulations were conducted using six different operation rule policies, as shown in Figure 2, to maximize the hydro energy generation. Alternative 1 operation rule was selected as a reservoir operation rule curve among the six alternative rules, on the basis of the energies and performance indicators criteria. On analyzing the outflow from the Sunkoshi III, the minimum release with operation policies in Scheme 1 is always greater than 67 m^3/s. Thus, the power production from the Sunkoshi III in Scheme 2 remains the same with the same performance parameters as in Scheme 1.

With actual irrigation deficit diversion during dry period only, the Alternative 5 operating policy produced the best results out of six alternatives. It produced a total annual average energy of 2956.6 GWh/year, including 657.1 GWh/year of dry energy. In a dry period, it provides 121 MW of firm power with 95% power reliability.

In the case of reservoir operation of Sunkoshi II in Scheme 2, the operation policy rule of Alternative 5 was selected, and the Elevation and Inflow-Outflow curve is shown in Figure 6.

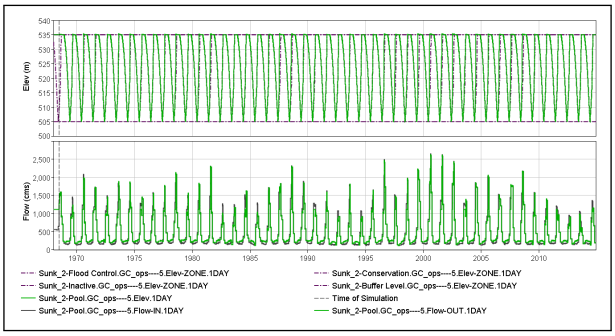

Figure 6: Reservoir elevation and inflow-outflow curves generated by reservoir Sunkoshi II operating in Alternative 5 policy of Scheme 2

When the diversion flow from SMDMP is limited, as shown in figure 7, to only meeting the actual water demand during the dry period, the SMDMP plant generates an annual energy of 219.4 GWh/year of which 95 GWh/year comes from dry period.

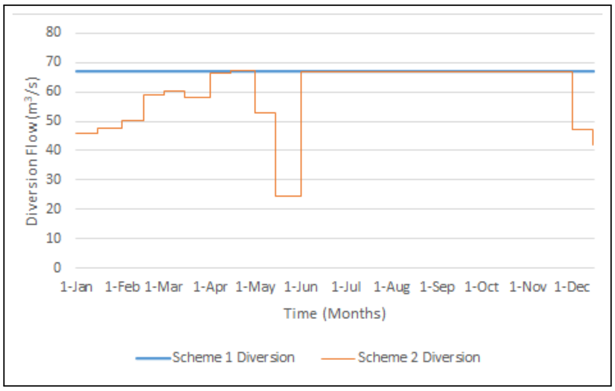

Figure 7: Sunkoshi Marin Diversion Multipurpose Project Release in two Schemes I and II

Thus, the system provides annual average energy of 5612.6 GWh/year of total energy, including an average dry energy contribution of 1433.3 GWh/year.

Scheme 3 findings: When SMDMP is excluded from the system, as in the other two schemes, the reservoir operation policy of Alternative 1 of Sunkoshi III generates the same magnitude of energy with the same PI. However, a significant increase in energy generation from the Sunkoshi II can be seen. The

Table 2: Difference in Energy Generations between Schemes

Project	Energy Diff. (Scheme 2-Scheme 1)		Energy Diff. (Scheme 3-Scheme 1)	
	Total Energy (GWH/year)	Dry (GWH/year)	Total Energy (GWH/year)	Dry (GWH/year)
Sunk III	0.0	0.0	0.0	0.0
Sunk II	56.3	56.3	442.6	242.4
SMDMP	-28.7	-28.7	-248.1	-123.7
Total	27.6	27.6	194.5	118.7

average annual energy generation capacity of Sunkoshi II will increase to 3342.9 GWh/year. Dry energy contribution will be of 843.2 GWh/year. This scheme will assure 161 MW of firm power with 95% power reliability during the dry period.

In the comparison of the schemes,as shown in table 2 it can be seen that energy generation and the PI criteria for Sunkoshi III remains the same in all three schemes. On differencing the schemes 2 on 1, the average annual dry energy of the Sunkoshi II has increased by 56.3 GWh/year and, hence the total energy. But, due to limited diversion in dry period, the SMDMP dry period energy is decreased by 28.7 GWh/ year. However, the tradeoff applied in scheme 2 has increased the system's dry energy production by 27.6 GWh/year. Similarly, exclusion of SMDMP from the Scheme 1 i. e. Scheme 3, has brought the significant rise in the total annual and dry energy from the reservoir Sunkoshi II. Even after deducting the energy generation capacity of SMDMP, the system will have an additional annual energy of 194.5 GWh/year. This is briefly presented in table 2.

5. Conclusions

The main aim of this research work was to model and simulate the proposed cascade dams of the Sunkoshi river and inter-basin transfer project and assess the tradeoff and relationships of the benefits (energy generation) of the different projects. The operation rules (policy) of the reservoirs were assessed to maximize energy generation while meeting the irrigation and other physical requirements. Specifically, it was intended for the policymakers and other stakeholders to assist in effective decision-making regarding projects in the Sunkoshi basin. HEC-ResSim was applied to simulate the trial coordinated operation rule to calculate the energy generation. The most optimal operation rule was chosen based on total energy, dry period energy, and performance evaluation criteria such as reliability, resiliency, and vulnerability. According to the simulation results, the sum of the average annual energy of system for the optimal operation rule in scheme 1 was calculated to be 5585.0 GWh. From the result of the alternatives, the operation rule curve which maintains full supply level elevation at the beginning of December has yielded more dry energy and total energy as well. Similarly, the performance evaluation criteria were also within the tolerance level. The result from Scheme 2 suggests that the additional dry energy of 27.6 GWh/year is generated by limiting the diversion to actual irrigation demand in the dry period. Also, if any projects downstream of Sunkoshi II are commenced then, this value of energy is sure to increase by multiple times. Hence, even if a single project is expected to be commissioned, the analysis of the projects identified in a basin should be done in an integrated manner, assessing trade-off among decision variables in the system.

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