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Uncertainty of Different Regional Models Hydrograph in Determination of Dam Height: A Case Study of Proposed Sisneri Water Supply Project

Sudarshan Sigdel [a], Narendra Man Shakya [b]

[a, b] *Department of Civil Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
[a] 078mswre017.sudarshan@pcampus.edu.np, [b] nms@ioe.edu.np

Abstract
Sisneri Water Supply project is a proposed alternative for minimizing the critical drinking water problem in the Kathmandu Valley by constructing a dam for storage of monsoon runoff so as to utilize it during dry season. The dam height is based on hydrology of the basin as well as socio-economic consideration. Since, Sisneri is an ungauged catchment so far, the hydrology of this basin has to be studied based on regional models and parameter transformation from hydrologically similar catchment. This study carries out the hydrological analysis for development of monthly hydrograph using different regional models (WECS/DHM, MHSP, MIP and Khosla) and a conceptual CRAWFORD model to determine conservation volume and select the height of reservoir based on reservoir reliability and proposed water demand from the source. The long-term daily flow generated by CAR is also used to simulate the reservoir on daily time series. There was seen a significant change in reservoir reliability when determined using CAR generated monthly flow and CAR generated daily flow. The results of this study show that, hydrograph from MIP method show insufficient runoff volume with a reservoir efficiency of 62.76%. The hydrograph output from other regional model showed surplus volume more than the deficit pertaining that 100% reservoir performance can be achieved. However, the height of reservoir was ranged from 81m to 94m from the long term monthly flow hydrographs by different regional models for 100% reservoir performance.

Keywords
Long term Monthly Flow Hydrograph, WECS, MHSP, MIP, Khosla, CAR, CRAWFORD, Reservoir Performance

1. Introduction

The ungauged basins are flawed by hydrological data for the analysis and require assessment from the hydrologically similar catchment for study either through streamflow statistics in relation with catchment properties or parameter borrowing from hydrologically similar gauged catchment [1] . The similarity in catchment is worked out based on spatial location and resemblance, catchment attributes and likeliness indices on structure of runoff generation and runoff routing [2]. Different regional equations are established from pools of gauged catchment for streamflow extrapolation within the catchment as well as for application in flow estimation of ungauged catchment hydrologically kindred. MIP Method, WECS/DHM Method and MHSP Method are the regional models developed in Nepal using regional analysis for monthly flow hydrograph estimation [3, 4, 5]. Khosla Formula is another regression equation developed by Khosla in 1960 for estimation of monthly flow which was developed from catchments of India and USA [6].

The conceptualization of hydrological phenomena is another means of analyzing hydrological process. Apart from relating rainfall-runoff statistically as in regression models and physically with laws of mass, momentum and energy conservation based on physics, the conceptual model uses an easy concept to represent the hydrological process [7]. CRAWFORD Model is the lumped conceptual model using water balance equation to represent the hydrological phenomena developed by Norman H. Crawford [8].

The objective of this study is to estimate the long-term mean monthly flow using different regional models and a conceptual model and using the estimated flow to determine the reservoir height for a proposed water supply scheme. The dead level is set to be 25% of gross volume for the analysis [9].

2. Materials and Methods

2.1 Study Area

The Sisneri catchment is a sub-basin of Bagmati River Basin. The coordinate of a proposed reservoir site is 85°13′40.5″E, 27°32′15″N which lie just upstream of a confluence in the vicinity of powerhouse of bagmati hydropower project. The catchment area is about 79.3 km^2. The climate of basin is warm temperate at most of its part and cool temperate at the higher elevation above 2100m. Figure 4 shows the location map of Sisneri catchment with diversions; Kulekhani reservoir, Sim Intake and Chakhel Intake and various hydro-meteorological stations in the vicinity of catchment. The basin receives 80% rainfall during the monsoon period that is brought up by bay of bengal. The catchment consists forest area, sparse settlement area, crop land, grass land and other wooded land.

- Water Body: 0.27%
- Forest: 72.89%
- Built-up Area: 0.5%
- Crop Land: 23.81%
- Grass Land: 1.27%
- Wood Land: 1.28%

No hydro meteorological stations lie within the catchment. In the vicinity of catchment, four precipitation stations and two climatological stations are available. 904, 915, 1015, 1075 and 1076 are the precipitation stations available nearest to the catchment. 905 and 1073 are the nearest climatological stations available nearest to the catchment.

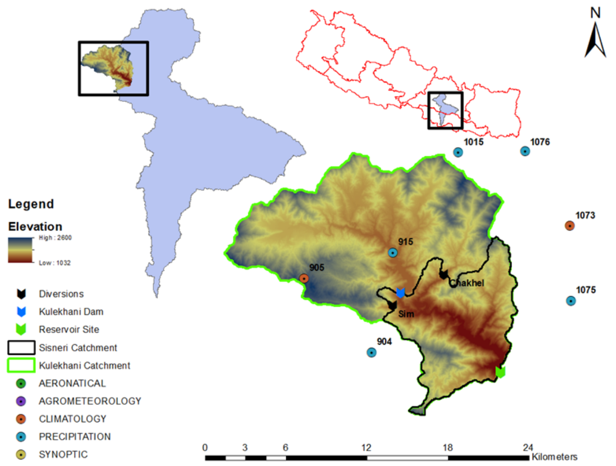

Figure 1: Location of the Catchment Area

2.2 Flow Computational Approach

2.2.1 Catchment-Area Ratio Method

Characteristics used in the study to evaluate the drainage area ratio method are drainage area, main channel slope and precipitation. The drainage-area ratio method assumes the stream flow or a site of interest multiplicative factor of the ratio of the drainage-area for the site of interest and the drainage area by the stream-flow for the nearby stream flow gauging station. Thus, drainage area ratio method is given by

$$Qy = Ay \times (Qx/Ax)$$

Where, Qy and Ay are discharge and area of the unknown location respectively. Qx and Ax are discharge and area at the measured location respectively

2.2.2 MIP Method

It is necessary to obtain one flow measurement in the low flow period from November to April for MIP method to estimate distribution of monthly discharge on ungauged locations. Non-dimensional hydrographs are developed by this method dividing the whole country into seven different regions. April flow is obtained by dividing the dry weather flow by corresponding non-dimensional ordinate and then, each ordinate of the required region is multiplied by the April flow to get the monthly hydrograph [3].

2.2.3 WECS/DHM Method

The WECS/DHM method use equation below to calculate mean monthly runoff with C, A_1, A_2 and A_3 as a monthly coefficient [4].

$$Q_{\text{mean}} = C \times (\text{basin area})^{A_1} \times (\text{basin area below } 5000 + 1)^{A_2} \times (\text{mean monsoon precipitation})^{A_3}$$

2.2.4 MHSP Method

The study by NEA found out total drainage area more statistically significant than area below 5000m from the study of 66 hydrometeorological stations and defined the new equation [5]. Coefficients C, A_1 and A_2 are the monthly coefficients.

$$Q_{\text{mean}} = C \times (\text{Basin Area})^{A_1} \times (\text{Mean Monsoon Precipitation})^{A_2}$$

2.2.5 CRAWFORD Model

The CRAWFORD Model uses water balance equation; Runoff = Rain Evapotranspiration + Change in Storage to conceptualize the hydrological phenomena of basin. Three parameters; NOMINAL, PSUB and GWF are used to generate monthly discharge data from rain data. Two reservoirs are conceptualized; storage of moisture (moisture storage) and reservoir of groundwater (groundwater storage). Changes to the reservoir are calculated as the difference from the final reservoir and early. Moisture storage is determined by rain and evaporation and excess moisture that becomes direct runoff and groundwater recharge. Groundwater storage is determined by groundwater recharge and ground flow that came out. The CRAWFORD parameter calibration stage is carried out with the aim of finding the most suitable parameter so that the calculated hydrograph is close to the observation. Since the main input of the model is rain, the calibration year depends on availability of rain data. In rivers that do not have flow data records, the rainfall data and Potential evapotranspiration can be used to calculate the discharge to flow sustainable. The calculation method uses rain data and monthly potential evapotranspiration and transform into monthly flow. Because monthly intervals are used, the routing process is ignored. The water balance equation is used every time interval, where rain, evaporation actual and runoff is the total volume of water entering and leaving the watershed at that time interval. Storage changes are changes in saturated groundwater in the time interval calculated by subtracting the final reservoir by the reservoir beginning. Water is held in soil moisture reservoirs, in layers groundwater, aquifers, and lakes [8]. Figure 2 shows the conceptual framework of CRAWFORD Model to better visualize how model is conceptualized with water balance phenomena.

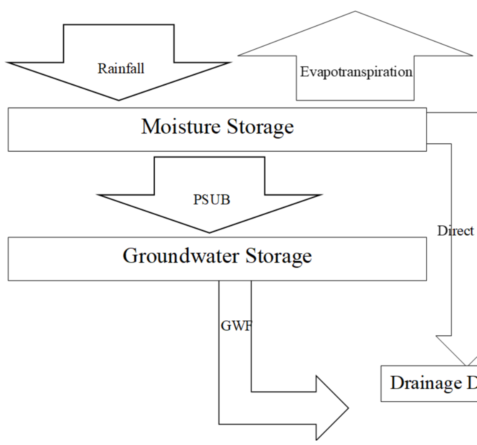

Figure 2: Conceptual Framework of CRAWFORD Model.

Direct Flow:

The calculation of direct runoff is determined based on excess rain that occurs on the surface taking into account potential evapotranspiration and infiltration [8].

$$\text{Direct Flow} = \text{Excess Moisture} - \text{Recharge to Ground Water}$$
$$= \text{Excess Moisture} \times (1 - \text{PSUB})$$

Excess Moisture:

Excess Moisture is calculated by multiplying the excess moisture ratio with the amount of water available based on the water balance which itself is calculated by subtracting actual evapotranspiration from precipitation [8].

$$\text{Excess Moisture} = \text{Excess Moisture Ratio} \times (\text{Precipitation} - \text{Actual Evapotranspiration})$$

Excess Moisture Ratio:

The value of the excess moisture ratio is determined based on the value of the comparison of soil moisture (soil moisture storage ratio) as shown in Figure 2. If the water balance value is greater than 0, then the value of the excess moisture ratio is same as given by graph. If the water balance value is less than 0, then the excess moisture ratio value is equal to 0. The curved line graph can be approximated by a mathematical equation as follows [8]:

$$\text{Excess Moisture Ratio} = 0.5 \times (1 + \tanh(\text{storage ratio of given month} - 1)/0.52)$$

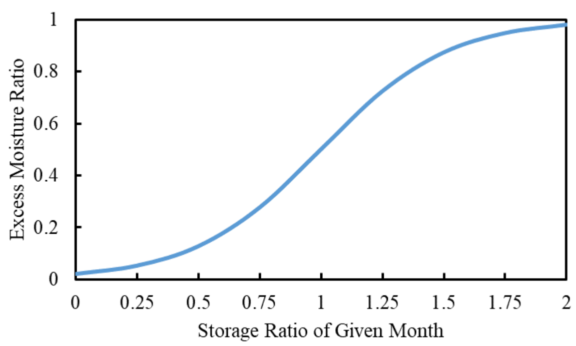

Figure 3: Relationship Between Excess Moisture Ratio and Soil Moisture Storage Ratio

The storage ratio is a comparison between the values of soil moisture storage with NOMINAL parameter. The value of the soil moisture storage is determined based on the condition of the value of initial conditions or from previous calculations while the NOMINAL parameter is determined by annual rainfall.

Actual Evapotranspiration:

The actual evapotranspiration is amount of water loss from soil moisture storage through evaporation and transpiration. The maximum water loss that could take place is potential evapotranspiration when there is sufficient soil moisture. AET is always less than or equal to PET under unavailability of sufficient soil moisture. As AET cannot be measured, it is determined from the graph between moisture storage ratio, precipitation and PET as shown in Figure 3. Calculation of the amount of AET which is determined based on PET is limited by storage ratio criteria and also Precipitation/PET following the principles shown

For a given month,
if SR < 2 and PPT/PET < 1,
AET/PET = (2-SR) x (PPT/PET)/2+SR/2<1,(2-SR) x (PPT/PET)/2+SR/2
else, AET/PET = 1

This relationship can also be repesented as in Figure 4.

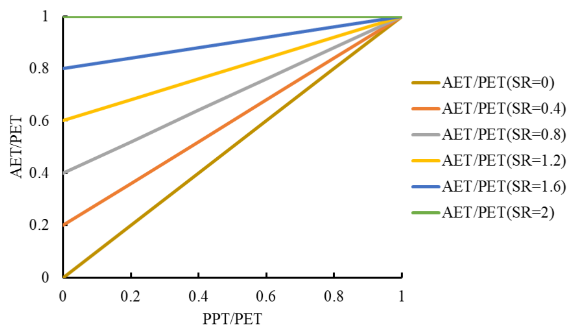

Figure 4: Relation of AET/PET and PPT/PET for Different Storage Ratio [8]

Ground Water Flow:

The groundwater flow flows to the river from groundwater storage. The fraction of water given by GWF will give the water added to stream through groundwater storage.

Ground Flow = GWF x (PSUB x Excess Moisture + Groundwater storage of previous month)

2.3 Data and Methodology

The total methodology in the research study was divided into three stages; mean monthly flow estimation, sediment yield estimation and reservoir height determination. Figure 5 shows methodological framework of the study.

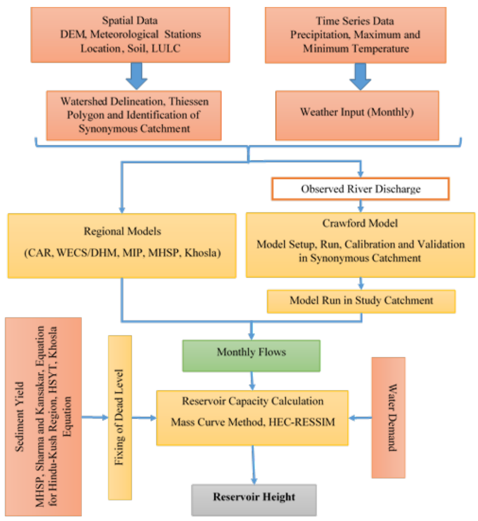

Figure 5: Methodological Framework of the Study

Table 1: Data Sources

S.N	Data	Data Type	Data Source
1	Topographical Data	DEM 30m by 30m resolution	ALOS World 3D [10]
2	Soil Data	Polygon Shapefile	SOTER [11]
3	Landuse Landcover Data	30m by 30m resolution 2019 A.D.	ICIMOD [12]
4	Precipitation	Daily	DHM
5	Temperature	Maximum and Minimum, Daily	DHM
6	Sunrise	Daily	DHM
7	Relative Humidity	Daily	DHM
8	Average Daily Discharge of Kulekhani Station	Daily	DHM

Table 2: Calculations for CRAWFORD Model Setup

SN	Parameter	Equation
1	Precipitation (PPT)	Observed Data collected from DHM
2	Potential Evapotranspiration (PET)	Using Thornthwaithe
3	AET/PET	(2-SR) x (PPT/PET)/2+SR/2<1,(2-SR) x (PPT/PET)/2+SR/2
4	AET	AET/PET x PET
5	Moisture Storage	Moisture Storage of Previous Month + Delta Storage
6	Storage Ratio	Soil Storage/NOMINAL
7	Water Balance	PPT-AET
8	Excess Moisture Ratio	0.5 x(1+ tanh((storage ratio of given month-1)/0.52))
9	Excess Moisture	Excess Moisture Ratio times Water Balance
10	Delta Storage	Water Balance - Excess Moisture
11	Recharge to Ground Water	PSUB x Excess Moisture
12	Initial Grounwater Storage	End Groundwater Storage - Groundwater Flow of Previous Month
13	End Ground water Storage	Initial Groundwater Storage + Recharge to Ground Water
14	Ground Flow	GWF x (PSUB x Excess Moisture + Groundwater storage of previous month)
15	Direct Flow	Excess Moisture x (1 - PSUB)
16	Total Flow	Direct Flow + Ground Water Flow

2.3.1 Long Term Average Monthly Flow Estimation

Different data required for mean monthly flow estimation by regional models and CRAWFORD model are listed in Table 1 with the source. Table 2 shows the calculations that are involved during CRAWFORD model setup.

The Kulekhani Basin was chosen a donor catchment whose parameter would be transposed to the ungauged catchment for flow estimation using Conceptual model. Kulekhani basin being the parent tributary of study basin, no snow contribution in both the basins, same type of dominant soils and almost similar LULC in both the basins and both the catchment with same topographical extent made Kulekhani Basin fit as a donor catchment. Figure 6, Figure 7, Table 3 and Table 4 show the similarity in soil map and LULC of study catchment and donor catchment.

The CRAWFORD Model was applied to the Kulekhani Basin, with calibration conducted using precipitation and hydrological data from 1972 to 1974. The validation phase encompassed 1975-1976. Calibration focused on three key parameters: NOMINAL, PSUB, and GWF, preceded by a two-year warm-up period. Model performance was assessed using indicators like NSE, PBIAS, RMSE, R2, and graphical representation to identify the best-fit parameter.

The parameters were transposed to ungauged catchment and the long-term monthly flow of an ungauged catchment was estimated.

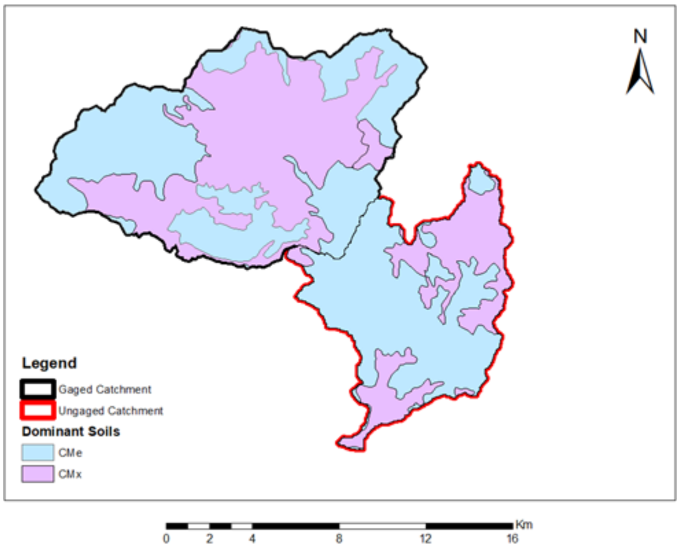

Figure 6: Soil Map of Donor and Study Catchment

Table 3: Soil Type Data

Soil Type	Kulekhani	Sisneri
Cme	49.1%	64.8%
CMx	50.9%	35.2%

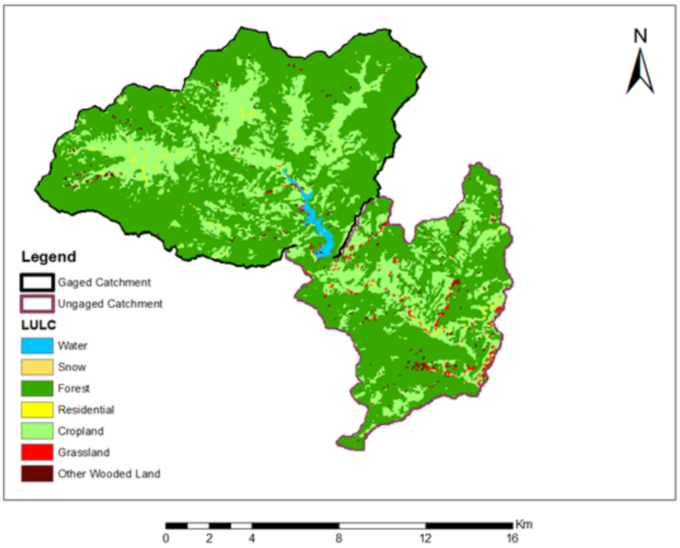

Figure 7: LULC map of Donor and Study Catchment

Table 4: LandCover Data

LandCover	Kulekhani	Sisneri
Forest	71.6%	67.2%
Residential Area	0.6%	0.6%
Cropland	27.0%	28.8%
Grassland	0.2%	2.1%
Other Wooded Land	0.7%	1.4%

2.3.2 Determination of Reservoir Height

The sediment yield for a period of 10 years was estimated by using equation developed by Sharma and Kansakar from twelve basins of mountainous regions of Nepal [13]. The equivalent volume of sediment yield from the equation for 10 years would be deposited to 1083m as per the area-volume-elevation curve of the region. Ten meter above sediment level was leftover as a buffer zone and the intake level was set at 1093m. The fixed parameter during determination of reservoir height was water demand and reservoir minimum pool level. Mass curve was used for reservoir sizing. The area-volume-elevation curve was developed for the reservoir from topographical survey data. No losses were considered in the analysis. Also, long-term daily average flow was estimated for a study catchment using CAR method and this flow estimate was used to simulate reservoir using HEC-RESSIM reservoir simulation model considering evaporation losses calculated using Thornthwaite equation [14] and environmental flow as per environmental protection act [15] to see the sensitivity of reservoir performance with flow time series.

3. Results and Discussions

3.1 Monthly Flow Estimation

The monthly flow of a catchment using different regional models and a CRAWFORD model is shown in Figure 8.

In CRAWFORD Model, parameters were best fitted with observed discharge in a donor catchment. Based on the performance indicators and visualization of graph, the values fixed to parameter are:

NOMINAL = 1440
PSUB = 0.45
GWF = 0.25

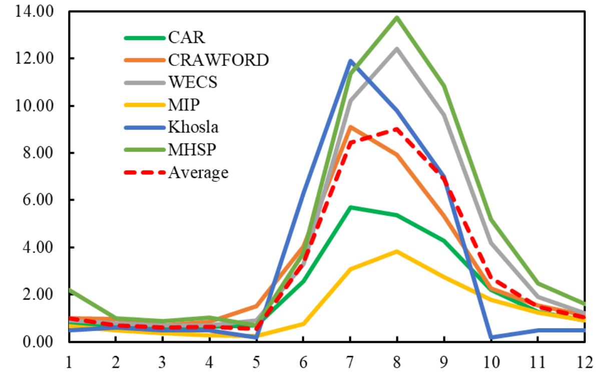

Figure 8: Monthly Flow Estimates from Different Regional Models

Table 6: Objective Functions for Calibration and Validation

Objective Functions	Calibration	Validation
R2	0.87	0.79
PBIAS	-6.27	-7.43
NSE	0.87	0.79
RMSE	2.32	2.10

Average monthly flow hydrograph in calibration period and validation period from observed data as well as simulated data is shown in the Figure 9 and Figure 10. Table 5 shows the performance of the model. The indicators show model performance to be excellent [16].

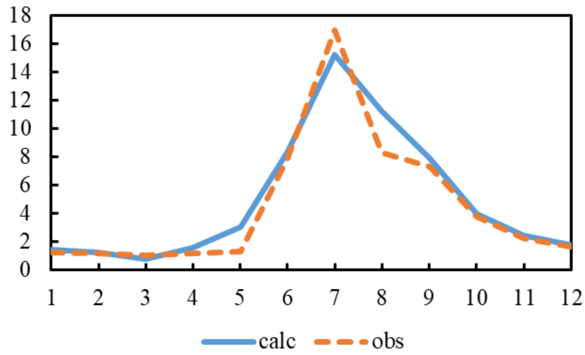

Figure 9: Average Monthly Flow Hydrograph for Calibration Period in Donor Catchment

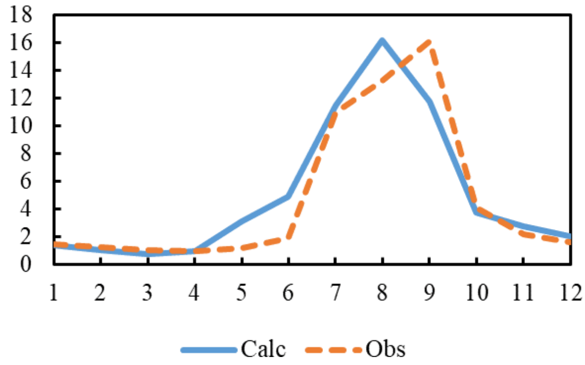

Figure 10: Average Monthly Flow Hydrograph for Validation Period in Donor Catchment

Table 5: Calculations of Reservoir Sizing and Reservoir Performance using Flow Estimates from Different Regional Models

Methods	WECS	MIP	Khosla	MHSP	CAR	Average	Crawford
Cumulative Deficit (MCM)	11.82	20.92	24.89	7.53	15	13.92	9.54
Cumulative Surplus (MCM)	84.52	13.13	75.51	101.34	31.9	59.15	54.56
Useful Reservoir Capacity (MCM)	11.82	13.13	24.89	7.53	15	13.92	9.54
Reliability (%)	100	62.76	100	100	100	100	100
Months Deficit	5	8	8	8	4	4	4
Months Surplus	7	4	4	4	8	8	8
Dead Storage (MCM)	2.53	2.53	2.53	2.53	2.53	2.53	2.53
Total Reservoir Storage (MCM)	14.35	15.66	27.42	10.06	17.53	16.46	12.08
Required Dam Crest RL for 100% Reliability	1131	1133	-	1123	1136	1135	1127

After fitting the parameters in a donor catchment, the parameters were transposed into the study catchment. Figure 11 shows the long-term average monthly flow hydrograph of a Sisneri catchment estimated from CRAWFORD Model.

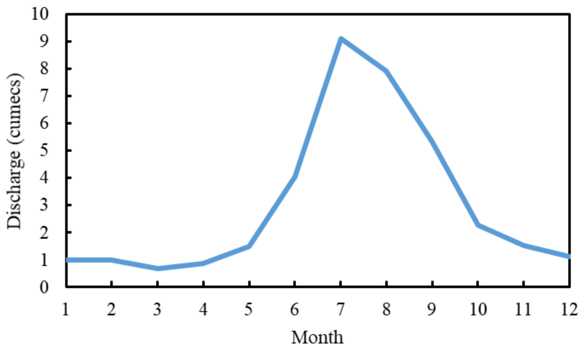

Figure 11: Flow Estimated by CRAWFORD Model in Study Catchment

3.2 Reservoir Size Determination

The capacity of reservoir to meet the demand of 140MLD was calculated using mass curve method with monthly flow estimated from different regional models. The flow estimated by MIP method show insufficient volume of water to meet the demand whereas all the other flow estimates show adequate volume of water to meet the demand. The reservoir height was seen to vary for different flow estimates from 81m to 94m. The case was considered with dam height restriction to 80m. On doing so, the reservoir efficiency from different flow estimates varied from 29.57% by Khosla flow estimate to 97.79% by MHSP flow estimate. Table 5 shows reservoir based calculations for different flow estimates.

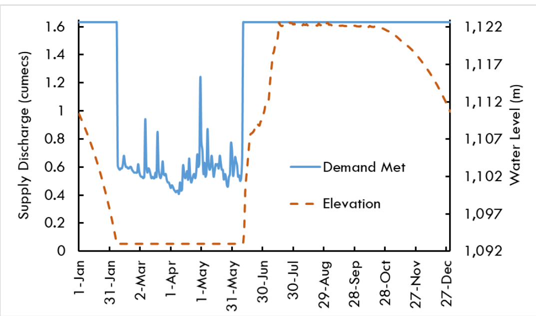

Figure 12: Reservoir Performance in Long Term Average Daily Flow Time Series When 140 MLD is Supplied until Minimum Drawdown and Runoff Equivalent Thereafter

Also, to see the reservoir performance on daily basis, reservoir was simulated in HEC-RESSIM using long term daily flow series calculated in reference to observed discharge of Kulekhani river and CAR method. The reservoir levels with corresponding supply of water from the simulation is shown in Figure 12. The reservoir operation rule considered for daily flow time series simulation was; flow shall be supplied until 140 MLD demand is met and then the runoff equivalent flow is supplied the other time. Upon this scenario, the reservoir efficiency was calculated to be 66.3%.

4. Conclusion

In this study, monthly flow estimation using regional and conceptual models revealed disparities among different regional equations. This led to the development of a daily flow model, and when reservoir storage limitations were imposed, both daily flow time series and monthly hydrographs showed significant reliability variations.

Acknowledgments

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