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Bi-directional Storage Capacity and Elevation Level Calculator for Reservoir Operation Management

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Abstract Reservoir management is an intricate task and the calculator proposed herein helps in assessing the storage in the reservoir using the elevation level. Based on the empirical values of storage capacity and levels the code developed here is able to generate bi-directional query by returning closest approximation corresponding to the given input. The closest approximation is heavily dependent on the resolution level of data for capacity versus elevation that is provided to the program. The efficacy of this code is tested on the data from Bhakra Dam. The code correlates the water level with the volume of water available in the reservoir. This precise assessment of available water will aid in the management of issues related to availability of water for agriculture, industry, hydropower, and domestic use among others. When the inflow and release volume is provided to the code as an input, it calculates the current water level and storage in dam. The output provided by the code can be utilized for effective operation of reservoir systems. The Bhakra Nangal and Beas project is a lifeline of the Northern states and its optimal operation by continuous monitoring of the available water will contribute to its better management.

Keywords: *reservoir, Bhakra, Satluj, python code, bi-directional*

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1. Introduction

Efficient operation of reservoirs is a challenging task due to stochastic nature of inflow. The objective of the present research is to develop a code that can be used for the operation of reservoirs in an efficient manner. The practicality of the approach developed herein is demonstrated through application to Bhakra reservoir located on Satluj River Basin – a key basin in the Himalayan region. The Satluj river originates from Mansarowar lake situated in Tibet at an elevation of about 4572 m and extends from 30° N to 33° N latitudes and 76°E to 83°E longitudes. It is one of the major rivers of the Indus system. In India Satluj river enters from Shipkila situated in Himachal Pradesh and flows in the South Westerly direction. The length of the river is approximately 1448 km. From Himachal Pradesh the Satluj river enters into the plain region at Bhakra located in Punjab. India's highest gravity dam is located at Bhakra situated in Punjab. It is a straight concrete gravity dam having 56,980 km^2 catchment area upstream of Bhakra dam. The height of the dam above the deepest foundation level is 225.55 m (740 ft). The height of the dam above river bed is 167.64 m (550ft). Govindsagar, the reservoir formed by the Bhakra Dam, has an area of 168.35km^2. The length of the reservoir is 96.56 km with a gross storage capacity of 9621 million cu.m, and live storage capacity of 7191 million cu.m. The minimum dead storage level to which the reservoir may be depleted is fixed at a mean sea elevation of 1462 ft (445.62 m) from irrigation and power generation considerations. The dam has ample spare capacity for silting during the expected life of the reservoir. The reservoir has an available capacity of 6 million acre-feet between the maximum reservoir level at 1690 ft (515.11 m MSL) and dead storage level at 1462 (445.62 m MSL) that can safely store the entire surplus flow of an average year.

2. Literature Review

Accurate estimation of reservoir level, storage, inflow and release are important parameters for deciding optimal operation policy of reservoirs. Reservoirs provide balance between the inflow, which are highly variable in time, and volume of water required to meet specific demand. In the past several procedures have been devised to estimate storage requirements. Reservoir inflow is estimated using conventional simple water balance equation. An analytical method based on simultaneous minimization of error in estimating reservoir water level and inflow variation was developed by [1]. A recursive filter based on state and observation equations was developed by G.Evensen [2]. [3] Estimated local inflows using the water balance equation and there after this methodology has been successfully applied in Ontario Hydro's new Energy and Resources Information System (ERIS) for the determination of daily

local inflows. [4] estimated reservoir capacity of Dibang Multipurpose Dam on Dibang River, Arunachal Pradesh using residual mass curve technique.[5] developed a model which can estimate current storage capacity of reservoir. The model developed by him is essentially an ASC curve which is based on Python script. This tool uses ArcPy site package and it works with triangulated irregular network (TIN) model.

[6] Amnatsan et al. developed a variation analogue method (VAM) for reservoir inflow forecasting which is able to capture the peak flows as rare extreme flows are crucial for effective reservoir management. The monthly inflows were also forecasted for Sirikit Dam, Thailand using wavelet artificial neural network (WANN) model, and the weighted mean analogue method (WMAM). However, better forecasts were obtained using the VAM model. The model was able to adequately capture extreme inflows at Sirikit Dam. [7] researcher used mass curve technique at Gizab multipurpose dam in Afghanistan to estimate maximum potential head and reservoir storage capacity. [8] Furnans, et al. described the utility of hydrographic survey. Authors have analyzed more than 100 bathymetric surveys of Texas reservoirs and estimated reservoir volumes and surface areas corresponding to reservoir stages. These surveys are also useful in estimating loss in capacity due to sedimentation over time.

[9] Alrayess, et al. developed a model to determine required reservoir capacity to meet demand for a given annual inflows using mass curve. Reservoir capacity-yield-reliability relationships were investigated for the Sami Soydam Sandalcik reservoir in Turkey. Data of monthly and annual mean flow for the duration 1962-2013 was used.

[10] Salih et al. used GIS to analyze the hydromorphometry of river basin. Based on 2D and 3D models of three sites. The maximum level, volume, surface area, circumference, shape factor of reservoirs is calculated. This experimental procedure can be used for any reservoir.

[11] EL-Hattab used bathymetric data to estimate the depth of channel. This depth will help to decide desired dredging and maintenance of channel in real time. For digital terrain modelling applications, it is concluded that a triangulated irregular network technique could be used. It is the fastest interpolation technique requiring only 0.35s to create a model with 5m grid size. [12] Rodrigues et al. used remote sensing data to estimate storage capacity of small reservoir in the Sao Francisco, Limpopo, Bandama and Volta river basins. [13] Khattab et al. developed bathymetric map of Mosul Lake by using a digital elevation model (DEM). In many developing countries, Bathymetric maps are still not available for lakes and reservoirs.

[14] explored the application of a deep learning algorithm, a recurrent neural network (RNN), long short-term memory (LSTM), and gated recurrent unit (GRU) to predict inflows and to do optimal reservoir operation for the Xiluodu (XLD) reservoir.

3. Appurtenances Used for Release of Water

The following facilities are available for discharging water to the downstream of the Bhakra Dam and the release can be estimated easily depending upon the appurtenances used for release.

- Penstocks
- River outlets
- Spillway

Out of these the discharge of water through the operating penstocks of the power plant is limited to the extent of power load coming on the turbine, while in the case of spillway the release is possible only when the reservoir is above the spillway crest level of 1645.211 ft.

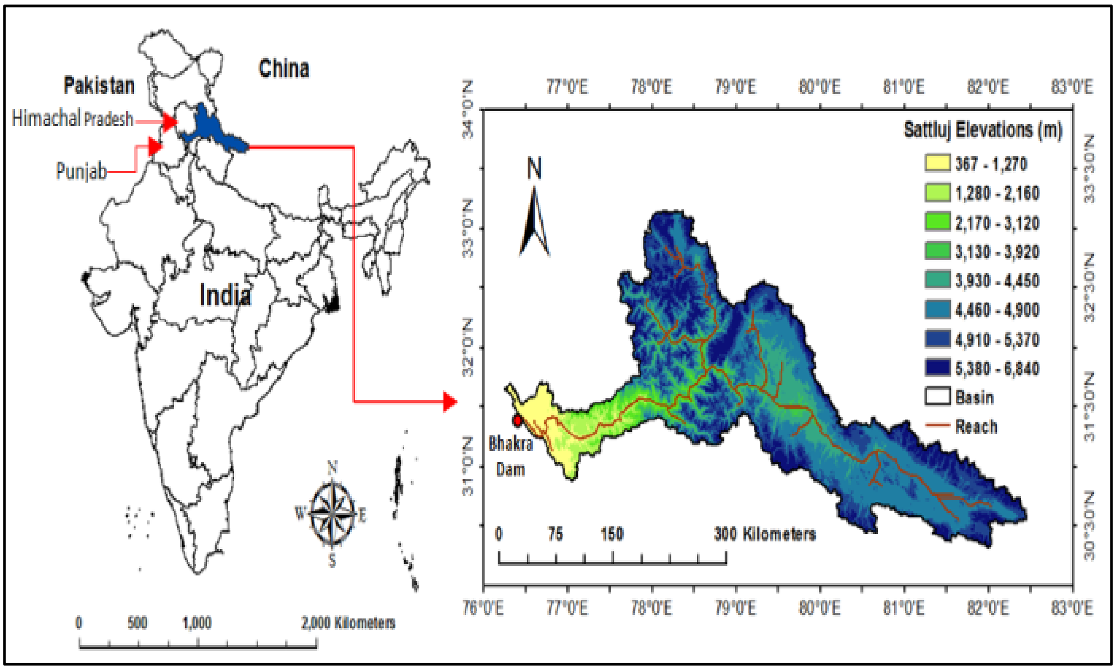


Figure 1. Schematic of Sutluj River Basin

3.1. Penstocks

Five penstocks are located on each side of the abutment. These are numbered from 1 to 5 on the left side, and 6 to 10 on the right side. The penstock are controlled automatically by the turbine wicket gates and for use in emergency. For the periodical shut down, head gates have been provided at the upstream end. Power output depends upon the:

- Difference in reservoir water elevation and tail water elevation.
- Discharge through one unit of the power plant.

Curves are prepared based on theoretical considerations and model results. Curves are modified according to actual performance of the units.

3.2. River Outlets

There are sixteen 96" (2438.4 mm) diameter outlets in the spillway portion of the dam located in two horizontal tiers of eight river outlets each, with centre lines at El. 1320 (402.34 m MSL) and EL 1420 (432.82 m MSL). These river outlets have been allotted numbers in a sequence from left to right, numbers 1 to 8 for El. 1420 (432.82 m MSL) tier of river outlets and 9 to 16 for El. 1320 (402.34 m MSL) tier of river outlets.

3.3. Spillway

The overflow spillway has crest level at El. 1645.21 ft (501.46 m MSL) and each of the four spillways is provided with radial gates for controlling the flow of water and disposal of floods. The spillway is located in the central block numbering 18, 19, 20, 21 and 22 of the dam. A central training wall divides the overflow spillway into two compartments for repair facilities. Tables are prepared which indicate discharge capacities for the spillway for various elevations of the reservoir water level with one and more gate open. Tables that indicate the quantity of water that will be released during part opening of the gates have been prepared.

There are sixteen river outlets main facility for releasing the water for irrigation and power indents downstream of Bhakra Dam. These river outlets in addition to the spillway are used for releasing the flood discharge. For operating the river outlet, jet flow gates are used. The spillway together with outlet can discharge 290000 cusecs of flood water. Inside the dam 5 Km long galleries are provided at various elevation for foundation grouting, drainage and inspection of the dam. A 9.14 m wide road is provided at the top of the dam.

4. Reservoir Storage and Area Information

Table 1 indicates the volume of water in million acre feet available and area in thousand acres at different elevations of the reservoir. Using contour maps and area covered at particular contour and using Trapezoidal or Simpson's rule, the reservoir storage capacity can be estimated. As per the present practice the capacity is calculated using the water level from the charts available. Curve plotted between the elevation in feet and capacity in million acre feet is shown in Figure 2. Another curve plotted between elevation in feet and area in thousand acres is shown in Figure 3.

Figure 4 indicates daily reservoir level, reservoir capacity in acre feet, inflow and release and Beas contribution. Beas contribution is water released from Dehar power plant. Table 2 indicates average monthly inflow and release for the duration 1999-2018.

Table 1. Elevation verses Storage and area data for Bhakra Dam Reservoir

Elevation in (feet)	Area in (thousand acres)	Capacity in (million acre feet)	Elevation in (feet)	Area in (thousand acres)	Capacity (million acre feet)
1150	0	0	1460	14.5	1.94
1180	0.21	0.002	1480	15	2.255
1200	0.65	0.011	1500	17.66	2.53
1220	1.5	0.033	1520	19.35	2.95
1240	2.35	0.073	1540	21.35	3.36
1260	3.25	0.123	1560	23.35	3.8
1280	4.43	0.203	1580	25.5	4.265
1300	5.8	0.305	1600	28.15	4.83
1320	7.18	0.435	1620	30.3	5.41
1340	8.25	0.585	1640	34.06	6.05
1360	9.33	0.755	1660	37.05	6.78
1380	10.3	0.95	1680	40.15	7.575
1400	11.25	1.17	1685	41	7.8
1420	12.18	1.4	1690	41.68	8
1440	13.35	1.665	1700	43.4	8.4

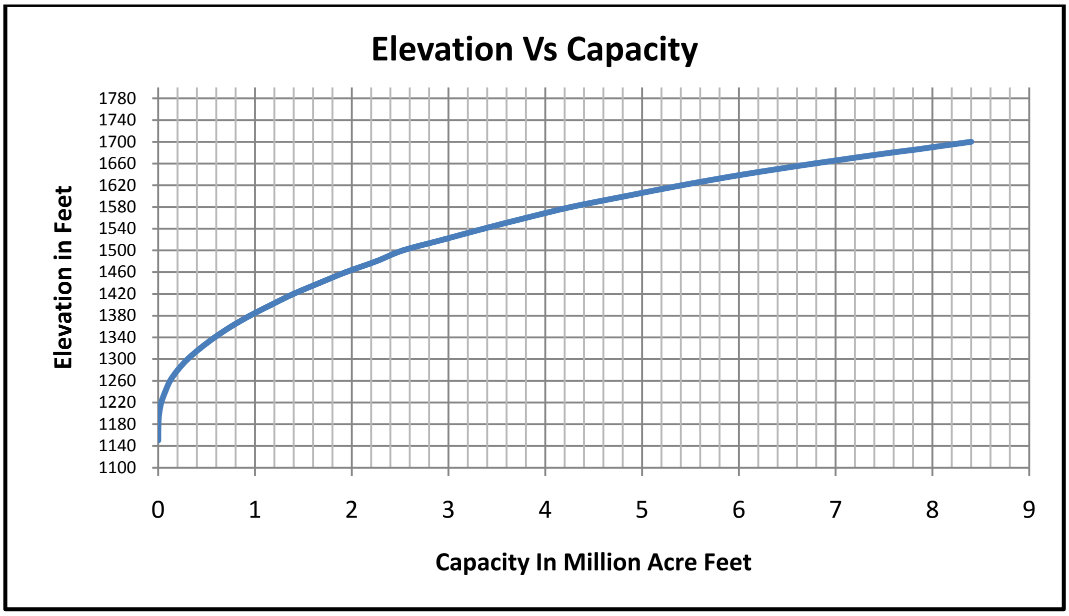


Figure 2. Plot between Elevation in Feet and Capacity in Million Acre Feet

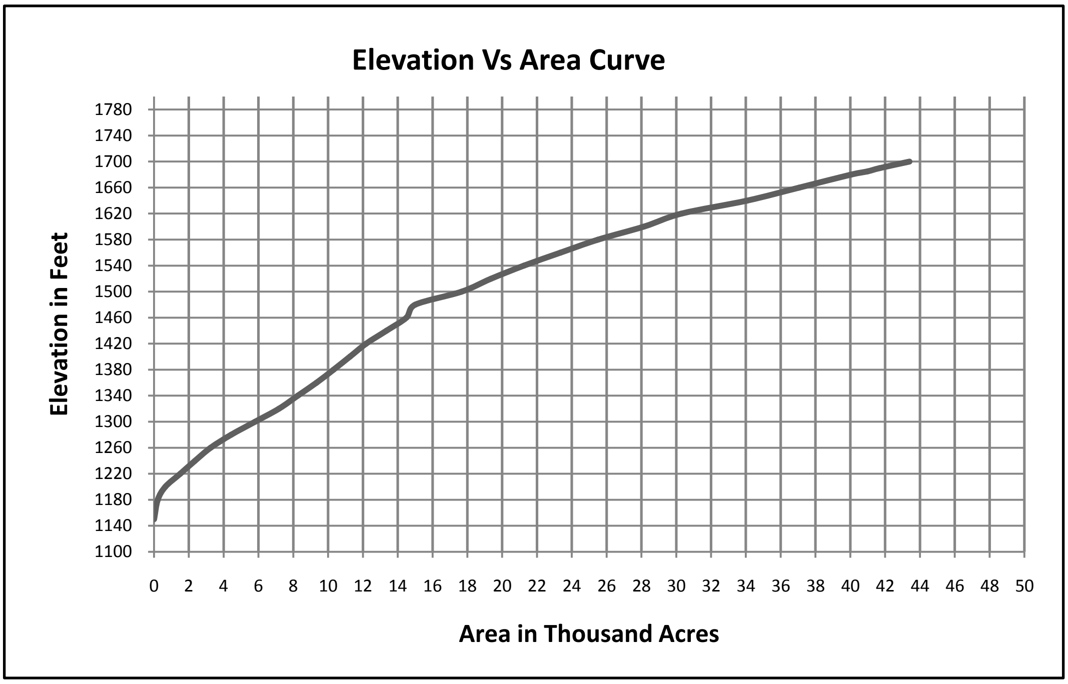


Figure 3. Curve showing plot between Elevation in Feet and Area in Thousand Acres

Figure 4. Hydrograph at Govind Sagar reservoir on 06.05.2017

Table 2. Average monthly Inflow and Release for Duration 1999-2018

Month	Average Inflow (cusec)	Average Release (cusec)
Jan	5563.655	16268.748
Feb	5622.869	16462.855
March	7412.779	16520.515
April	10994.627	13083.947
May	21847.358	21337.329
June	32920.228	26791.300
July	45904.458	26695.740
August	48152.744	25014.700
September	27006.712	22218.412
October	12181.473	16075.484
November	7717.747	15153.195
December	6218.531	16667.690

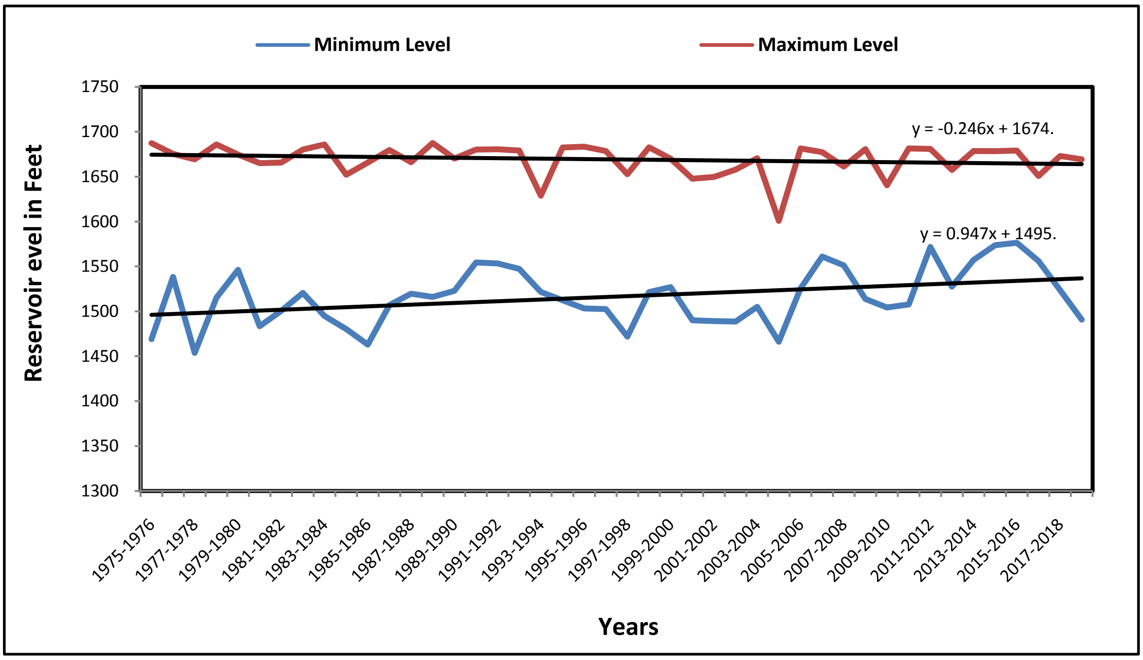


Figure 5. Reservoir yearly Minimum and Maximum level

Figure 5 indicates the reservoir minimum and maximum level in feet for duration 1975 -2019.

The dead storage level of reservoir is at an elevation of 1462 ft, whereas the maximum reservoir elevation is 1680 ft. In order to mitigate floods the reservoir level can be raised up to elevation of 1690 ft in consultation with Chairman BBMB. It is observed from Figure 5 that the water level reaches maximum storage elevation of 1680 ft every year by 31 August. from 1975 to 2019 except in few years. Figure 5 also indicate no significant change in maximum or minimum levels from 1975 to 2019.

5. Bhakra Reservoir Capacity Calculator

The Python script uses binary search to predict various parameters of Bhakra reservoir. Binary search is half-interval search algorithm that predicts the position of a target value within a sorted array. Binary search compares the target value to the middle element of the array. In binary search, an array is sorted by repeatedly dividing the search interval in half. From excel sheet data, the Python script is able to locate the volume corresponding to a particular elevation. The code automatically updates the status of reservoir with time. Initial water level data is fed to code and the corresponding closest reservoir capacity is evaluated depending upon the resolution of the data.

Water balance equation

$$S_{t+1} = S_t + Q_{t+1} - R_t \quad (1)$$

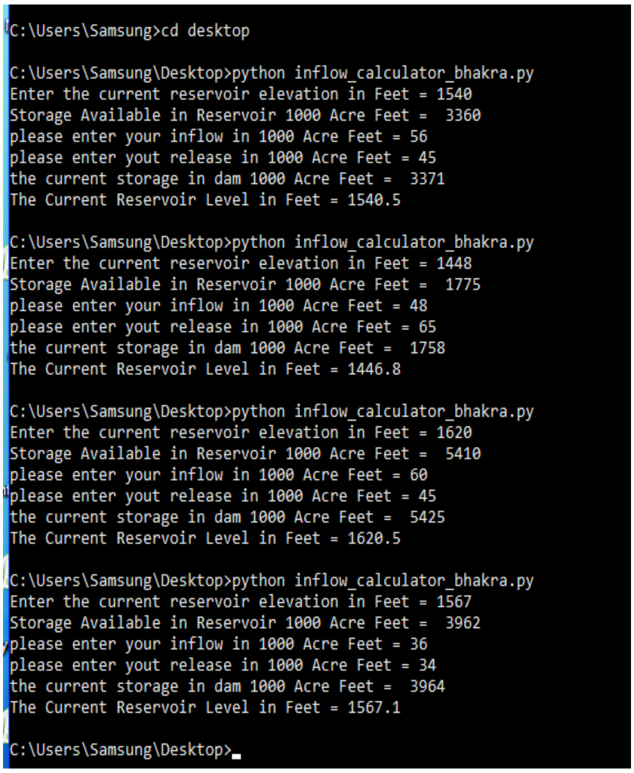
S_{t+1} is storage at time (t+1) in thousand acre feet, Q_t is the total inflow volume (thousand acre feet) in time t and R_t is the total release volume (thousand acre feet) from the dam in time t.

$$R_{t\,max} \leq S_t + Q_{t}. \quad (2)$$

Present storage S(t+1), previous storage St can be estimated from Python script from measured levels which are monitored continuously. Release depending upon demand is a known parameter. Inflow volume Qt can be determined using the following equation.

$$Q_t = S_{t+1} - S_t + R_t \quad (3)$$

Figure 6 shows the results obtained after executing the python script inflow_calculator_bhakra.py. The results indicate the computation of reservoir capacity when reservoir level is provided to code. When inflow volume and release is fed in the code, it provides next state of reservoir storage and its level.


```
C:\Users\Samsung>cd desktop

C:\Users\Samsung\Desktop>python inflow_calculator_bhakra.py
Enter the current reservoir elevation in Feet = 1540
Storage Available in Reservoir 1000 Acre Feet =  3360
please enter your inflow in 1000 Acre Feet = 56
please enter yout release in 1000 Acre Feet = 45
the current storage in dam 1000 Acre Feet =  3371
The Current Reservoir Level in Feet = 1540.5

C:\Users\Samsung\Desktop>python inflow_calculator_bhakra.py
Enter the current reservoir elevation in Feet = 1448
Storage Available in Reservoir 1000 Acre Feet =  1775
please enter your inflow in 1000 Acre Feet = 48
please enter yout release in 1000 Acre Feet = 65
the current storage in dam 1000 Acre Feet =  1758
The Current Reservoir Level in Feet = 1446.8

C:\Users\Samsung\Desktop>python inflow_calculator_bhakra.py
Enter the current reservoir elevation in Feet = 1620
Storage Available in Reservoir 1000 Acre Feet =  5410
please enter your inflow in 1000 Acre Feet = 60
please enter yout release in 1000 Acre Feet = 45
the current storage in dam 1000 Acre Feet =  5425
The Current Reservoir Level in Feet = 1620.5

C:\Users\Samsung\Desktop>python inflow_calculator_bhakra.py
Enter the current reservoir elevation in Feet = 1567
Storage Available in Reservoir 1000 Acre Feet =  3962
please enter your inflow in 1000 Acre Feet = 36
please enter yout release in 1000 Acre Feet = 34
the current storage in dam 1000 Acre Feet =  3964
The Current Reservoir Level in Feet = 1567.1

C:\Users\Samsung\Desktop>
```

Figure 6. Screen shot of the results produced by the code

Table 3. Elevation verses Storage Capacity at Bhakra

	Volume in Thousand Acre Feet																	
Elevation in Feet	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
1400	1170	1181.9	1193.8	1205.7	1217.6	1229.5	1241.4	1253.3	1265.2	1277.1	1.19	2.38	3.57	4.76	5.95	7.14	8.33	9.52	10.71
1410	1289	1309.9	1312.8	1324.7	1336.6	1348.5	1360.4	1372.3	1384.2	1396.1	1.19	2.38	3.57	4.76	5.95	7.14	8.33	9.52	10.71
1420	1408	1420.9	1433.7	1446.6	1459.4	1472.3	1485.1	1498	1510.8	1523.7	1.29	2.57	3.86	5.14	6.43	7.71	9	10.28	11.57
1430	1536.5	1549.4	1562.2	1575.1	1587.9	1600.8	1613.6	1626.5	1639.3	1652.2	1.29	2.57	3.86	5.14	6.43	7.71	9	10.28	11.57
1440	1665	1678.8	1692.5	1706.3	1720	1733.8	1747.5	1761.3	1775	1788.8	1.38	2.75	4.13	5.5	6.88	8.25	9.63	11	12.38
1450	1802.5	1816.3	1830	1843.8	1857.5	1871.3	1885	1898.8	1912.5	1926.3	1.38	2.75	4.13	5.5	6.88	8.25	9.63	11	12.38
1460	1940	1955.8	1971.5	1987.3	2003	2018.8	2034.5	2050.3	2066	2081.8	1.58	3.15	4.73	6.3	7.88	9.45	11.03	12.6	14.18
1470	2097.5	2113.3	2129	2144.8	2160.5	2176.3	2192	2207.8	2223.5	2239.3	1.58	3.15	4.73	6.3	7.88	9.45	11.03	12.6	14.18
1480	2255	2271.3	2287.5	2303.8	2320	2336.3	2352.5	2368.8	2385	2401.3	1.63	3.25	4.88	6.5	8.13	9.75	11.38	13	14.63
1490	2417.5	2433.8	2450	2466.3	2482.5	2498.8	2515	2531.3	2547.5	2563.8	1.63	3.25	4.88	6.5	8.13	9.75	11.38	13	14.63
1500	2580	2598.7	2617.3	2636	2654.6	2673.3	2691.9	2710.6	2729.2	2747.9	1.87	3.73	5.6	5.6	9.33	11.19	13.06	14.92	16.79
1510	2766.5	2785.2	2803.8	2822.5	2841.1	2859.8	2878.4	2897.1	2915.7	2934.4	1.87	3.73	5.6	5.6	9.33	11.19	13.06	14.92	16.79
1520	2953	2973.4	2993.7	3014.1	3034.4	3054.8	3075.1	3095.5	3115.8	3136.2	2.04	4.07	6.11	8.14	10.18	12.21	14.25	16.28	18.32
1530	3156.5	3176.9	3197.2	3217.6	3237.9	3258.3	3278.6	3299	3319.3	3339.7	2.04	4.07	6.11	8.14	10.18	12.21	14.25	16.28	18.32
1540	3360	3382	3404	3426	3448	3470	3492	3514	3536	3558	2.2	4.4	6.6	8.8	11	13.2	15.4	17.6	19.8
1550	3580	3602	3624	3646	3668	3690	3712	3986	3756	3778	2.2	4.4	6.6	8.8	11	13.2	15.4	17.6	19.8
1560	3800	3823.3	3846.5	3869.8	3893	3916.3	3939.5	3962.8	3986	4009.3	2.33	4.65	6.98	9.3	11.53	13.95	16.28	18.6	20.93
1570	4032.5	4055.8	4079	4102.3	4125.5	4148.8	4172	4195.3	4218.5	4241.8	2.33	4.65	6.98	9.3	11.53	13.95	16.28	18.6	20.93
1580	4265	4293.3	4321.5	4349.8	4378	4406.3	4434.5	4462.8	4491	4519.3	2.83	5.65	8.48	11.3	14.13	16.95	19.78	22.6	25.43
1590	4547.5	4575.8	4604	4632.3	4660.5	4688.8	4717	4745.3	4773.5	4801.8	2.83	5.65	8.48	11.3	14.13	16.95	19.78	22.6	25.43
1600	4830	4859	4888	4917	4946	4975	5004	5033	5062	5091	2.9	5.8	8.7	11.6	14.5	17.4	20.3	23.2	26.1
1610	5120	5149	5178	5207	5236	5265	5294	5323	5352	5381	2.9	5.8	8.7	11.6	14.5	17.4	20.3	23.2	26.1
1620	5410	5442	5474	5506	5538	5570	5602	5634	5666	5698	3.2	6.4	9.6	12.8	16	19.2	22.4	25.6	28.8
1630	5730	5762	5794	5826	5858	5890	5922	5954	5986	6018	3.2	6.4	9.6	12.8	16	19.2	22.4	25.6	28.8
1640	6050	6086.5	6123	6159.5	6196	6232.5	6269	6305	6342	6378.5	3.65	7.3	10.95	14.6	18.25	21.9	25.55	29.2	32.85
1650	6415	6451.5	6488	6524.5	6561	6597.5	6634	6670.5	6707	6743.5	3.65	7.3	10.95	14.6	18.25	21.9	25.55	29.2	32.85
1660	6780	6819.8	6859	6899.3	6939	6978.8	7018.5	7058.3	7098	7137.8	3.98	7.95	11.93	15.9	19.88	23.85	27.83	31.8	35.78
1670	7177.5	7217.3	7257	7296.8	7336.5	7376.3	7416	7455.8	7495.5	7535.3	3.98	7.95	11.93	15.9	19.88	23.85	27.83	31.8	35.78
1680	7575	6720	7665	7710	7755	7800	7840	7880	7920	7960	4.5	9	13.5	18	22.5	27	31.5	36	40.5

6. Conclusions

Python software based inflow calculator will enable the engineers and policy makers to determine the storage available in the dam based on water levels measured at gauging stations daily. The levels in the dam can be effectively monitored hourly during peak flows in filling period with the help of the script developed herein. Continuous monitoring of reservoir storage is necessary in order to ensure effective flood mitigation. Dam is required to be emptied to absorb excess flow. Release from the dam depends upon the demand, storage available and downstream capacity to absorb flow. Inflow can also be assessed from the water balance equation. The software described in the present paper has the potential to enable continuous monitoring of the reservoir state. Using the software developed here, human error in the operation of Bhakra reservoir can be completely eliminated.

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