Optimizing the water allocation jointly for Jayakwadi Dam (Nath Sagar Reservoir) and Dudhana Dam to maximize the revenue generated.

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Introduction

The Jayakwadi Dam is an earthen dam constructed on the Godavari River near Jayakwadi village in Paithan taluka, located in the Aurangabad district of Maharashtra, India. The dam forms the Nath Sagar Reservoir, which is one of the largest multipurpose water projects in the state. The primary objective of this project is to provide water for irrigation in the drought-prone Marathwada region. Additionally, the reservoir supplies water for industrial purposes and helps fulfill the domestic water needs of the surrounding population.

The Dudhana Dam, located in Aurangabad district, is built on the Dudhana River, a tributary of the Godavari. Though smaller in scale, it plays a crucial role in supporting local water demands, especially for domestic and agricultural purposes.

In this analysis, we address the joint water allocation problem involving both Nath Sagar and Dudhana reservoirs. These reservoirs cater to multiple sectors in Aurangabad and Ahmednagar districts, including irrigation, drinking water supply, and industrial use.

Our primary goal is to develop an optimal water allocation strategy that maximizes the economic returns from these limited water resources. Given that Aurangabad lies within the Nath Sagar catchment and Ahmednagar is in close proximity to the Dudhana Dam, both districts are included in the study. By considering historic data, evaporation losses, and sector-wise revenue generation, we aim to formulate a robust allocation model that reflects the socio-economic priorities of the region.

For our analysis we have used the **Purpose Driven Study (PDS) conducted by the Hydrology Project Division, Aurangabad Water Resources Department, Government of Maharashtra in June 2010.**

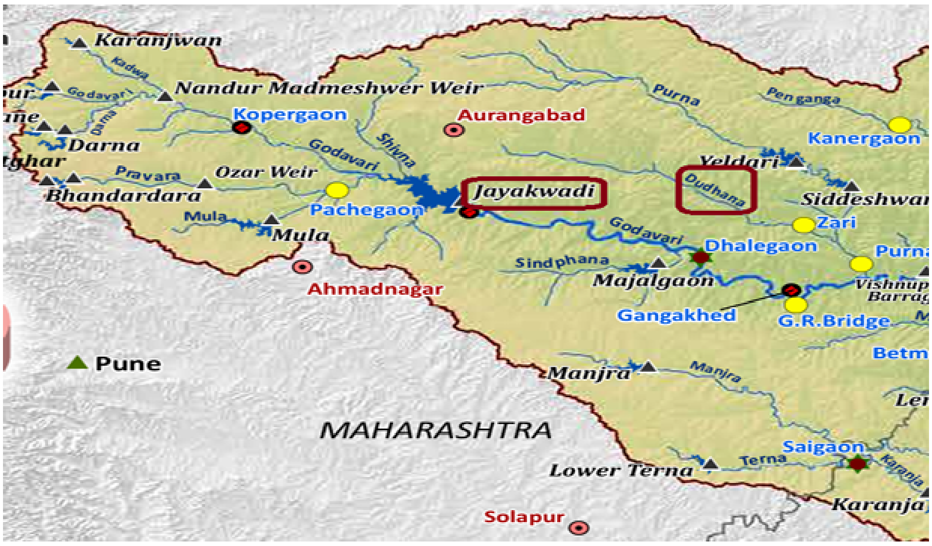

Figure 1: Map showing region of Interest
Source: Water Resources Department, Government of Maharashtra

Methodology

To estimate the maximum amount of water that can be supplied by the reservoirs, we have used the 50% dependable yield of the Nath Sagar Reservoir (Jayakwadi Dam) instead of its maximum storage capacity of 2909 million cubic meters (Mm^3). The yield of a reservoir is defined as the maximum volume of water that can be safely released over a specific period (typically one year) without lowering the reservoir below critical levels. It is determined based on several factors including inflow (from rainfall and upstream contributions), reservoir capacity, seepage losses, operational constraints, and historical inflow records.

The 50% dependable yield refers to the amount of water that is equaled or exceeded in 50% of the years in the historical data—effectively serving as a median yield i.e., there is 50% probability that reservoir has water more than the given quantity. For the Jayakwadi Dam, this valueis 2105 Mm^3. A similar approach is applied to the Dudhana Dam, where the live yield is considered to be 242 Mm^3.

We could have also used the average yield over the years, which was 2456 Mm^3, but since the median is less than the mean, it shows that the region has a higher probability of receiving less than average rainfall.

In the dataset we used, government authorities have treated 2170 Mm^3 as the planned or design yield for Jayakwadi, rather than its full storage capacity. Therefore, for planning, we consider 2170 Mm^3 as the effective usable volume. The same principle applies to the Dudhana Dam.

For simplicity of the project we have considered three uses of the reservoir waters– (1) Irrigation (2) Industrial (3) Domestic. The water is supplied to them by both Jayakwadi Dam and Dudhana Dam and so we are jointly optimizing the water allocation for maximum profit.

Network Diagram: Network diagram is as follows:

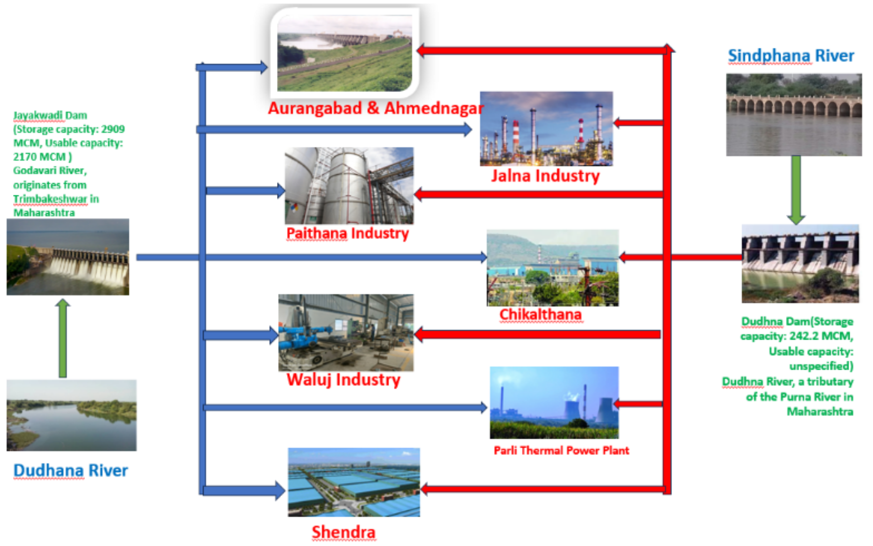

Figure 2: The network Diagram.

Objective

To maximize total revenue generated by all sources.

Variables (in Mm^3)

- x_1: Water supplied by Jayakwadi dam for irrigation
- x_2: Water supplied by Jayakwadi dam for industry
- x_3: Water supplied by Jayakwadi dam for domestic use
- y_1: Water supplied by Dudhana dam for irrigation
- y_2: Water supplied by Dudhana dam for industry
- y_3: Water supplied by Dudhana dam for domestic use

Revenue Tables

Table 1: Break up for Revenue Generation for Irrigation

Year	2006-07	2007-08	2008-09	2009-10
Water Used (Mm^3)	1166.65	1148.98	1350.04	333.61
Gross Revenue (lakhs)	645.31	1678.4	3411.76	1281
Revenue per Mm^3	0.55	1.46	2.52	3.85

- Average = (0.55 + 1.46 + 2.52 + 3.85) / 4 = **2.905 lakhs/Mm^3**

Table 2: Break up for Revenue Generation for Industrial purposes

Year	2006-07	2007-08	2008-09	2009-10
Water Used (Mm^3)	97.357	201.456	208.786	125.404
Gross Revenue (lakhs)	5089.2	8757.86	5010.87	6898.22
Revenue per Mm^3	52.46	43.47	24.08	55

- Average = (52.46 + 43.47 + 24.08 + 55) / 4 = **43.75 lakhs/Mm^3**

Calculation for Revenue Generated by Municipal Corporation for Fulfilling Water Demand

Population Statistics (According to 2011 Census)

- Population of Aurangabad: 1,175,116 $\approx$ 1.2 million
- Population of Ahmednagar: 4,543,159 $\approx$ 4.5 million

Municipal Water Charges

According to data obtained from the Maharashtra Pollution Control Board:

- Maximum municipal water charges for domestic purposes = 3 paise per kiloliter
- = 0.3 lakhs per Mm^3

Annual Water Demand in the Region of Interest

Population Distribution:

- Aurangabad: Predominantly urban population
- Ahmednagar: 80% rural, 20% urban

Daily Water Demand per Individual:

- Rural Area:

$$30\ \text{(bathing)} + 5\ \text{(drinking)} + 35\ \text{(cooking, laundry, miscellaneous)} = \textbf{70 liters}$$

- Urban Area:

$$\text{Similar to rural (70 liters)} + 30\ \text{(gardening, extra clothing, etc)} = \textbf{100 liters}$$

Total Daily Water Demand in Region of Interest:

$$(1.2 \times 10^6 \times 100) + (0.8 \times 4.5 \times 10^6 \times 70) + (0.2 \times 4.5 \times 10^6 \times 100)$$

$$= 120 \times 10^6 + 252 \times 10^6 + 90 \times 10^6 = \textbf{462 million liters} = \mathbf{0.462\ Mm^3}$$

Effective Demand Met by Reservoirs

Since there are alternative water sources (e.g., groundwater, rainwater) and infrastructural constraints (e.g., lack of canals or pipelines), we assume:

- **Reservoirs satisfy only 40%** of annual water needs.

$$\text{Annual water demand met by reservoirs} = 0.4 \times 0.462\ \mathrm{Mm}^3 \times 365 = \mathbf{67.45\ Mm^3}$$

Note

This is the **minimum requirement** by the population of the region. It is reasonable to assume that **human consumption increases with availability**, and any surplus water provided will likely be consumed without restraint.

Objective Function

Maximise $Z = \sum P_i \cdot x_i$, where
P_i = per unit profitability of operation i, and
x_i = amount of water allocated to operation i.
In our context,

$$\text{Maximize } Z = 2.905(x_1 + y_1) + 43.75(x_2 + y_2) + 0.3(x_3 + y_3)$$

This objective function determines the total revenue generated via different sectors, which include:

- Irrigation
- Industries
- Domestic use

From the above analysis, the average revenue or cost per Mm^3 of water used is as follows:

- **Irrigation** – 2.905 lakhs per Mm^3
- **Industries** – 43.75 lakhs per Mm^3
- **Domestic Use** – 0.3 lakhs per Mm^3

From analysing the historical data (1975-2009) given PDS report of Govt. of Maharashtra, we had excluded the data of 1975-76 as it was the very first year after construction of the dam and its data seemed outlier.

Constraints (in Mm^3)

$$\begin{aligned}
206.032 \leq x_1 + y_1 &\leq 1616.620 && \text{(water allocated for irrigation)} \\
19.331 \leq x_2 + y_2 &\leq 208.786 && \text{(water allocated for industrial purposes)} \\
x_3 + y_3 &\geq 67.45 && \text{(water allocated for domestic use)} \\
x_1 + x_2 + x_3 &\leq 1724.74 && \text{(water allocated from Jayakwadi Dam)} \\
y_1 + y_2 + y_3 &\leq 193.6 && \text{(water allocated from Dudhana Dam)}
\end{aligned}$$

How Constraints Were Derived

- Table 10.1 of document released by Water Resource Department of Maharashtra Govt. has data of Irrigation and Non - Irrigation consumption of water from 1975 to 2009. We can see from this table that the minimum requirement of water for irrigational use was in year 1987-88 which is 206.032 Mm^3 and maximum requirement of water for irrigational use was in year 1991-92 which is 1616.620 Mm^3.

- Similarly we can see that for Industrial purpose minimum yield of water was 19.331 and maximum yield was 208.786..

- For domestic use the calculations is already shown above.

- Now the Live storage of Jayakwadi dam with 50 percentile value is 2105 Mm^3. From the same document we get to know that when the water stored is nearly 100storage which is 2170Mm^3, evaporation loss was 392Mm^3. So for 2105 Mm^3 of filled reservoir, the water evaporated is linearly interpolated and found to be:- 392/2170 * 2105 Mm^3 = 380.26Mm^3 So maximum water supplied from Jayakwadi dam = 2105-380.26 = 1724.74Mm^3

- Similarly for Dudhana Dam the live storage capacity is 242 Mm^3. Approximately 20is evaporated. So the maximum water supply from Dudhana Dam = 242-0.2*242 = 193.6Mm^3

  Thus we found out a total of 5 constraints.
  N = Total no. of variables = 6
  m = Total no.of constraints = 5

Data Sources

Purpose Driven Study (PDS) conducted by Hydrology Project Division, Aurangabad Water Resources Department, Government of Maharashtra in June 2010.

Available at: https://www.slideshare.net/slideshow/mh-sw-effect-of-changing-water-allocation-in-nathsagar-project-jayakawadi-dam-paithon-district-aurangabad/34371373

Table 10.1
IRRIGATION & NON-IRRIGATION USE

Year	Actual Live Storage	Total withdrawal from reservoir Mm3	Irrigation use	% w.r.t. Live storage	Non-irrigation use (Industry + domestic)	N.I Use % compared to withdrawal from Storage	N.I Use % compared to Design Live Storage (2170.935 Mm3)
1975-76	135.250	171.03	167.261	97.8	3.769	2.2	0.17
1976-77	1162.350	252.601	249.108	98.6	3.493	1.4	0.16
1977-78	939.170	199.35	195.863	98.3	3.487	1.7	0.16
1979-80	695.800	541.311	536.009	99	5.302	1	0.24
1980-81	1468.250	724.801	718.245	99.1	6.556	0.9	0.30
1981-82	602.000	920.737	910.478	98.9	10.259	1.1	0.47
1982-83	1600.020	1123.986	1110.372	98.8	13.614	1.2	0.63
1983-84	1210.550	951.749	938.365	98.6	13.384	1.4	0.62
1984-85	2037.910	1124.718	1108.313	98.5	16.405	1.5	0.76
1985-86	1751.340	710.818	690.279	97.1	20.539	2.9	0.95
1986-87	663.240	231.852	209.281	90.3	22.571	9.7	1.04
1987-88	304.600	225.363	206.032	91.4	19.331	8.6	0.89
1988-89	475.230	1240.405	1219.024	98.3	21.381	1.7	0.98
1989-90	2041.610	1384.537	1364.608	98.6	19.929	1.4	0.92
1990-91	1976.040	1321.139	1290.322	97.7	30.817	2.3	1.42
1991-92	2171.000	1654.772	1616.62	97.7	38.152	2.3	1.76
1992-93	1678.620	401.028	342.07	85.3	58.958	14.7	2.72
1993-94	690.340	780.521	732.295	93.8	48.226	6.2	2.22
1994-95	763.100	1684.28	1632.05	96.9	52.23	3.1	2.41
1995-96	1913.950	254.077	180.75	71.1	73.327	28.9	3.38
1996-97	306.110	434.654	379.805	87.4	54.849	12.6	2.53
1997-98	770.453	775.397	702.832	90.6	72.565	9.4	3.34
1998-99	1068.789	914.28	844.024	92.3	70.256	7.7	3.24
1999-00	2126.758	1140.439	1071.96	94	68.479	6	3.15
2000-01	2167.353	951.963	879.951	92.4	72.012	7.6	3.32
2001-02	1281.731	349.387	269.809	77.2	79.578	22.8	3.67
2000-03	494.169	244.364	137.674	56.3	106.69	43.7	4.91
2003-04	404.373	291.307	137.213	47.1	154.094	52.9	7.10
2004-05	392.687	1101.042	923.518	83.9	177.524	16.1	8.18
2005-06	2129.141	1374.937	1232.268	89.6	142.669	10.4	6.57
2006-07	2170.935	1757	1166.65	66.36	97.357	5.5	4.48
2007-08	2170.935	1872.912	1148.98	61.37	201.456	10.73	9.28
2008-09	2170.935	2069.45	1350.044	65.24	208.786	10.08	9.62

Figure 3: Table 10.1 from the report showing yearwire irrigation and non-irrigation use

Table 7.1

Actual Evaporation Losses (Mm^3)

(Under nearly full storage condition)

Year	% Live	Evaporation losses (Mm^3)			
	Storage	Kharif	Rabi	H.W.	Total
1983-84	94	63	129	319	511
1988-89	94	35	138	206	379
1989-90	91	90	124	180	394
1990-91	100	85	130	238	453
1998-99	98	58	96	229	383
1999-2000	100	99	109	206	414
2005-06	100	-	-	-	337
2006-07	100	-	-	-	343
2007-08	100	-	-	-	313
				Average	**392**

Figure 4: table 7.1 from PDS report showing Evaporation losses when reservoir was nearly full.

Results and Discussion

Table 3: Optimised value of variables obtained.

Variable	Value(in Mm^3)
x_1	1616.62
x_2	15.186
x_3	92.934
y_1	0
y_2	193.6
y_3	0

- Table 3 clearly shows that profitability in the industrial sector dominates other sectors.
- The water supply for domestic uses (92.934 Mm^3) is more than the required level (67.45 Mm^3), which indicates a potential wastage of water.
- The land and industries are underutilised.

Revenue Generated = Rs. 13858.55 Lakhs

In Figure 4 shown below, the constraints with slack/surplus value = 0 are the binding constraints. The graph of constraints is plotted in Desmos. We can see the valid regions over here.

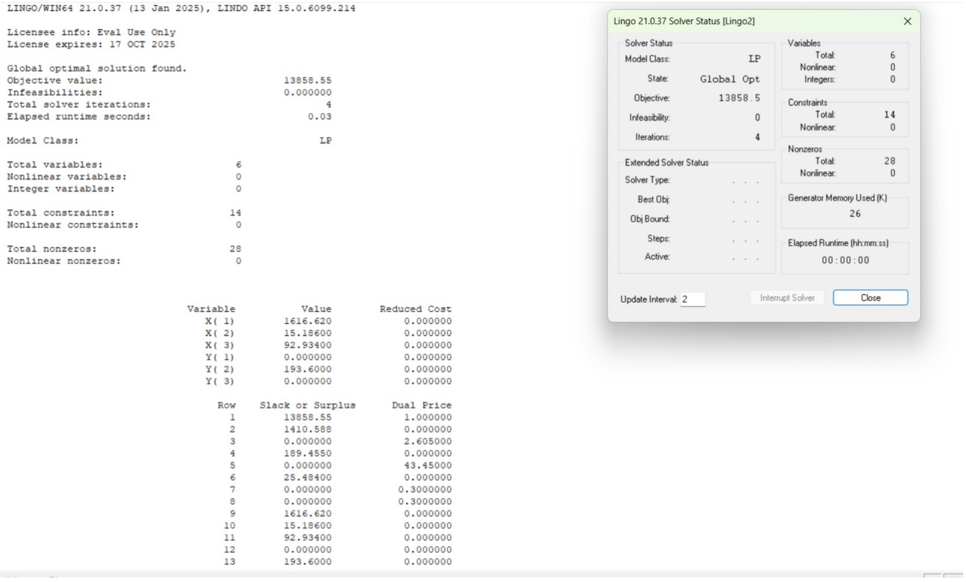

Figure 4: Result as obtained in LINGO..

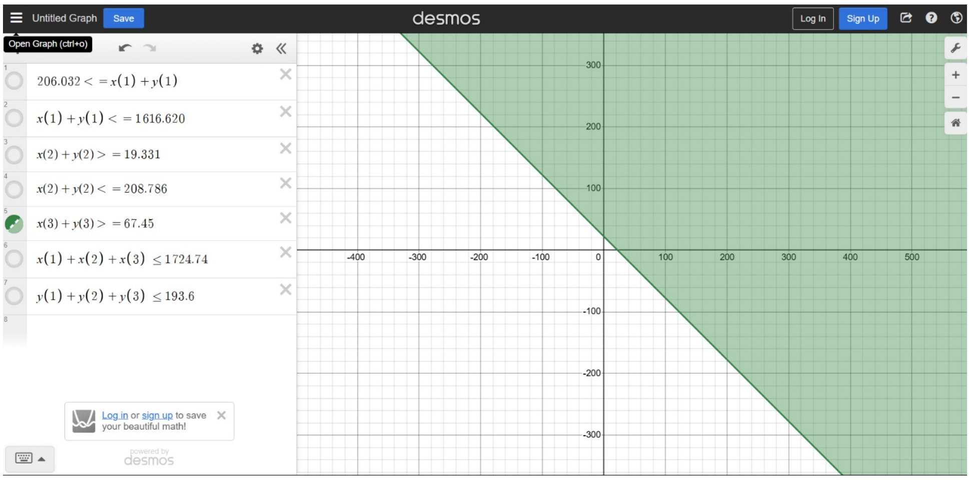

Figure 5: Here we are plotting the first constraint and observing the valid region

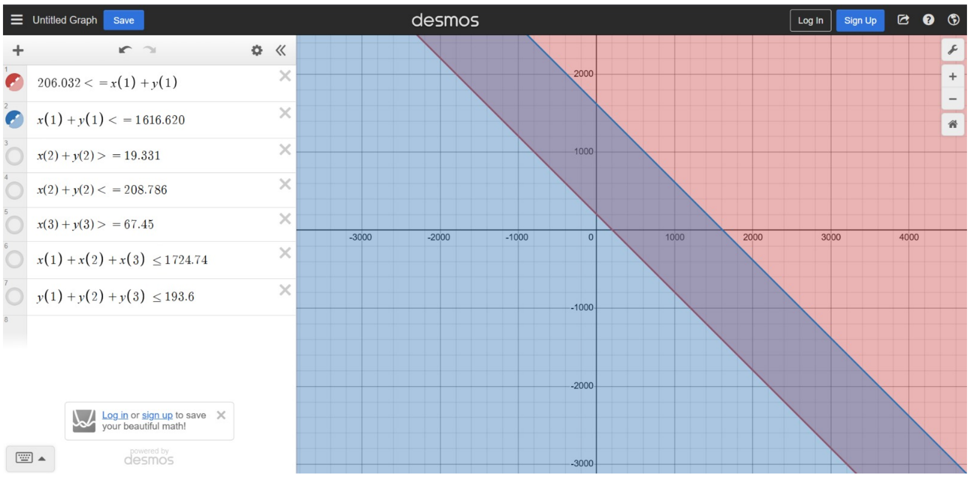

Figure 6: Here we are plotting the second constraint and observing the valid region

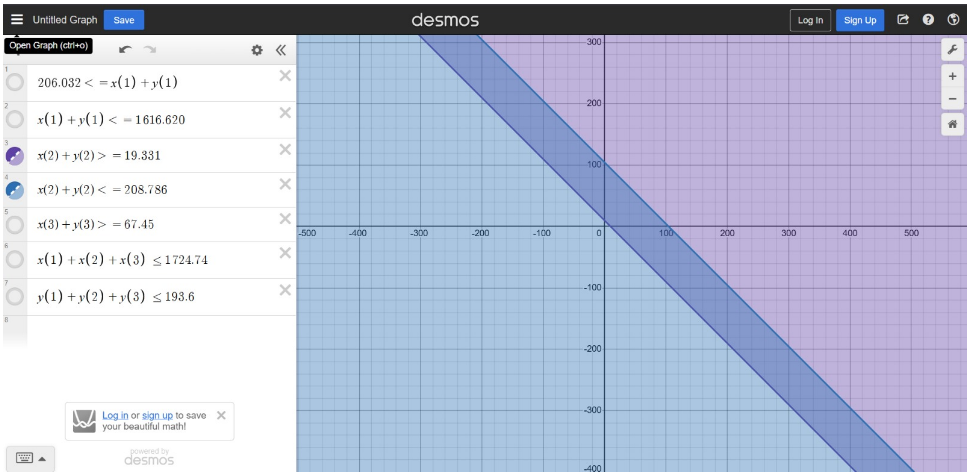

Figure 7: Here we are plotting the third constraint and observing the valid region

Conclusions

- After analyzing the report, we observed that industrial activities hold significant potential for contributing to the region's economic growth. However, as referenced in the section 10.5 of the PDS report and based on discussions with officials from the Maharashtra Industrial Development Corporation (MIDC), water availability is currently not a limiting factor for industrial development. This suggests that the region's challenge lies not in water supply, but in the lack of adequate infrastructure to fully capitalize on industrial opportunities.

- (The following finding is obtained from analysis of PDS report) Furthermore, as highlighted in Section 7.2.1 of the PDS report, the planned irrigation efficiency was estimated at 49the actual efficiency achieved was only 21and inefficient irrigation practices currently in use.

- To enhance regional revenue, the government should prioritize the development of industrial infrastructure while simultaneously promoting sustainable irrigation methods such as drip irrigation and sprinkler systems, which can improve water use efficiency in agriculture.

- Regarding domestic water usage, no specific recommendations can be made to reduce demand, as minimum domestic consumption is non-negotiable. However, steps can be taken to reduce the burden on reservoir storage by encouraging rainwater harvesting and local water recharge initiatives across the region.

LINGO Code

```
! MODEL TITLE: Optimizing Water Distribution from Jayakwadi and
   Dudhana Dams jointly;
model:

sets:
S /1..3/: x, y;
endsets

! Sectors: 1 = Irrigation, 2 = Industry, 3 = Domestic;
! Dams: x = Jayakwadi, y = Dudhana;

! Objective Function;
MAX = 2.905*(x(1)+y(1)) + 43.75*(x(2)+y(2)) + 0.3*(x(3)+y(3));

! Constraints;
x(1) + y(1) >= 206.032;
x(1) + y(1) <= 1616.620;

x(2) + y(2) >= 19.331;
x(2) + y(2) <= 208.786;

x(3) + y(3) >= 67.45;

@sum(S(i): x(i)) <= 1724.74;
@sum(S(i): y(i)) <= 193.6;

! Non-negativity;
@for(S(i): x(i) >= 0);
@for(S(i): y(i) >= 0);

end
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