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A RESERVOIR MANAGEMENT OPERATION SYSTEM BASED ON FAILURES IN THE ATTENDANCE OF THE WATER DEMAND

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Abstract. This paper presents a system called REMO (reservoir management operation), developed in C++ programming language, which is capable to estimate the reservoir active storage capacity and the regulated flow using an adaptation of the behavior or simulation analysis method. The reservoir critical period was defined as the time interval from the full condition through emptiness to the full condition again; releasing the regulated discharge and using the total active storage. The proposed methodology also permits to attribute failures in the attendance of the water demand, considering the historical records. To validate the methodology, simulations on Sobradinho and Boa Esperança hydropower reservoirs were performed. The first one is located on São Francisco River, Bahia State, and the second on Parnaíba River, Piauí State. The regulated discharges estimated by REMO were compared with the values published by Companhia Hidro Elétrica do São Francisco, and the differences were above 0,4% in Sobradinho and equal to 0% in Boa Esperança. REMO proved to be an excellent tool to help the water manager during the decision process to choose the best alternative to increase the water availability in basins with scarcity or where the future requirements may cause a water stress.

1 INTRODUCTION

The new Brazilian water resource policy brought an innovation in the management, organizing and planning of water use in river basins, especially the instruments provided for its implementation, as the water right. The use is authorized after the water availability analysis, represented by the balance between offer and demand among the users, indicating a situation of stress or abundance in the river basin. The offer is represented by the maximum surface water withdrawal and is equal to 70% from $Q_{95\%}$ discharge (equaled or exceeded 95 percent of the time) or 50% from $Q_{7,10}$ discharge (average minimum seven-day duration with recurrence interval of ten years), depending on the federal or state government water agency criteria. When this natural resource is scarce, alternatives to increase the water availability should be studied and the most usual solution is to allocate water for multiple uses (reservoir storage), regulating the downstream flow.

According to Villela and Mattos (1975), a reservoir accumulates water in rain periods to compensate the drought sequence of the low-flow periods, regulating the downstream flow. Thus, the storage size required depends on three factors; the variability of the river flows, the size of the demand, and the degree of reliability of this demand being met (McMahon and Mein, 1978). The reservoir capacity determinates the water uses, represented by the regulated discharge (Hora, 2008).

The specific purpose of the present work was to conceive a computational tool nominated REMO (Reservoir Management Operation) which estimates the size of storage required to meet a given demand, considering a probability of failure. The software also calculates the regulated and average discharges from the historical inflow data.

2 SELECTED DESIGN METHOD

The design capacity of a reservoir can be estimate by several methods. Those related to critical period techniques as Rippl Diagram, residual mass curve and simulation analysis are widely applied.

The selected design method was the behavior or simulation analysis, where the changes in storage content of a finite reservoir are calculated using a mass storage equation, as defined in McMahon and Mein (1978), thus:

$$Z_{t+1} = Z_t + Q_t - D_t - \Delta E_t \text{ , subject to } 0 \leq Z_{t+1} \leq C \tag{1}$$

where:

Z_{t+1}	storage at end of the t^{th} time period or storage at beginning of $t+1^{th}$ period.
Z_t	storage at beginning of t time period.
Q_t	inflow during t^{th} time period.
D_t	release during t^{th} time period.
ΔE_t	net evaporation loss from reservoir during t^{th} time period. The net evaporation loss is the difference between the evaporation from the proposed reservoir and the evapotranspiration from the proposed reservoir site and depends on the surface area of water in the reservoir.
C	active storage capacity.

It is assumed that the reservoir is initially full; the historical data sequence is representative of future river flows; and it is possible to set a storage size for which the reservoir just empties once for the period of historical data. It is also assumed that the critical period corresponds to the time interval from the full condition through emptiness to the full condition again (USACE, 1975).

3 OPERATION RULE

The reservoir operation considered two approaches of release rule (Hora, 2008):

- Reservoir level in the end of t-1th period is situated between maximum and minimum pool level: the reservoir is in a condition of drawdown (depletion) or refilling, so the outflow is equal to regulated discharge (Qrel = Qreg).
- Reservoir level in the end of t-1th period is equal to maximum level: the reservoir is filled, so the outflow is equal to spillway discharge plus regulated discharge (Qrel = Qspill + Qreg).

According to Hora (2008), regulated discharge represents the average flow possible to be released constantly, from the full condition (100%) through emptiness (0%) to the full condition again (100%), using all of the active storage capacity, as illustrated in Figure 1. It is calculated by iteration process, balancing both sides of equation (2):

$$\sum_{t}^{t_1}(Q\inf - Qreg) = \Delta V_{max} + |\Delta V_{min}| \tag{2}$$

$$\Delta V_{max} + |\Delta V_{min}| = C \tag{3}$$

where:

$Q\inf$	inflow discharge, in m^3/s.
$Qreg$	regulated discharge, in m^3/s.
ΔV_{max}	maximum accumulated difference between inflow and release, in m^3.
$\lvert\Delta V_{min}\rvert$	minimum accumulated difference between inflow and release, in m^3.
C	active storage capacity, in m^3. Represents the water stored above the level of the lowest off take (total storage minus dead storage).

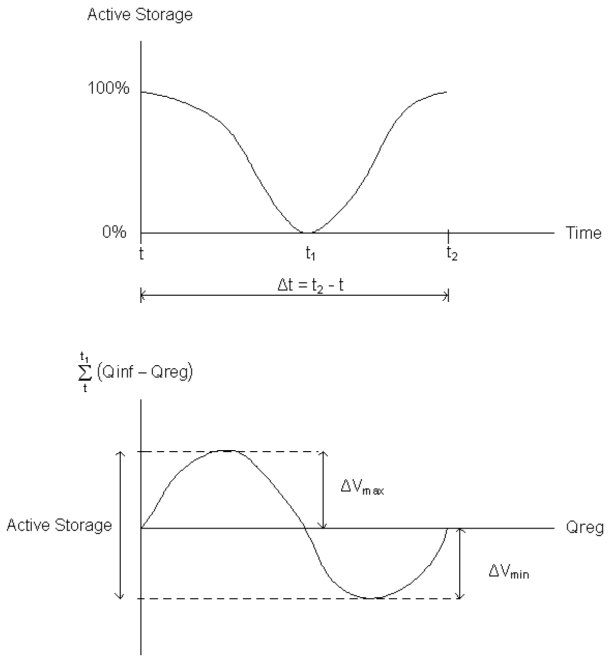


Figure 1: Regulated Discharge and Active Storage Capacity (Hora, 2008)

The active storage capacity is given as:

$$V_t = V_{t-1} + (Q\inf_t \cdot ns) - (Qrel_t \cdot ns) - Ve_t \text{, subject to } 0 \le V_t \le C \tag{4}$$

$$Qevap = \frac{Ve_t}{ns} \tag{5}$$

$$S_t = \frac{V_t}{C} \cdot 100 \tag{6}$$

where:

V_t	storage at the end of t time period, in m^3.
V_{t-1}	storage at the end of t-1th period, in m^3.
$Q\inf_t$	inflow during tth time period, in m^3/s.
$Qrel_t$	release during tth time period, in m^3/s.
Ve_t	net evaporation during tth time period, in m^3.
$Qevap_t$	net evaporation discharge during tth time period, in m^3/s.
S_t	storage at the end of t time period, in percentage.
ns	number of seconds in a month and equal to 2.6298×10^6.

The reservoir pool level can be calculated by the following equation:

$$N.A_t = \left(\frac{N.A_{t-2} + N.A_{t-1}}{2} \right) \tag{7}$$

where:

$N.A_t$	pool level at the beginning of t time period, in m.
$N.A_{t-2}$	pool level at the end of t-2 time period, in m.
$N.A_{t-1}$	pool level at the end of t-1 time period, in m.

The reservoir surface is estimated by the pool elevation (N.A) vs reservoir surface (A) curve. The net evaporation loss is defined as:

$$Ve_t = EL_t \cdot A \cdot 1000 \tag{8}$$

$$EL_t = Ew_t - ETR_t \tag{9}$$

where:

Ve_t	net evaporation loss, in m^3.
A	reservoir surface, in km^2.
EL_t	net evaporation during tth time period, in mm.
ETR_t	real evapotranspiration during tth time period, in mm. Estimated by Morton's CRAE model, (Morton, 1983; Hora and Marques, 2010; Noronha, 2007).
Ew_t	lake evaporation during tth time period, in mm. Estimated by Morton's CRLE model, (Morton, 1983; Hora and Marques, 2010; Noronha, 2007).

4 PROBABILITY OF FAILURE

If storage capacity is not a limitation, the capacity of a proposed reservoir can be adjusted until the system meets the design demand without failure, and in this case the design demand is equal to the regulated discharge.

If the reservoir cannot meet the required the demand, it means demand is above the regulated discharge, thus it is necessary to estimate the probability of failure, defined as the proportion of time units during which the reservoir cannot satisfy the demand to the total number of time units used in the analysis. Hence:

$$Pe = \frac{p}{N} \cdot 100 \tag{10}$$

where:

Pe probability of failure, in percentage.
p number of time units during which the demand is not satisfied.
N total number of time units in the stream flow sequence.

The active storage capacity is calculated by iteration, fixing the demand, until the probability of failure defined by the user is met. The storage can be estimated by:

$$S = \frac{V_t}{C_{Pe}} \cdot 100 \tag{11}$$

where:

C_{Pe} active storage capacity for a defined probability of failure, in m^3.

Other restrictions can be placed limiting the reservoir size and introducing a probability of failure, such as social and environmental externalities (large inundation areas interfering in wildlife or villages). The proposed methodology considers the sketch shown in Figure 2.

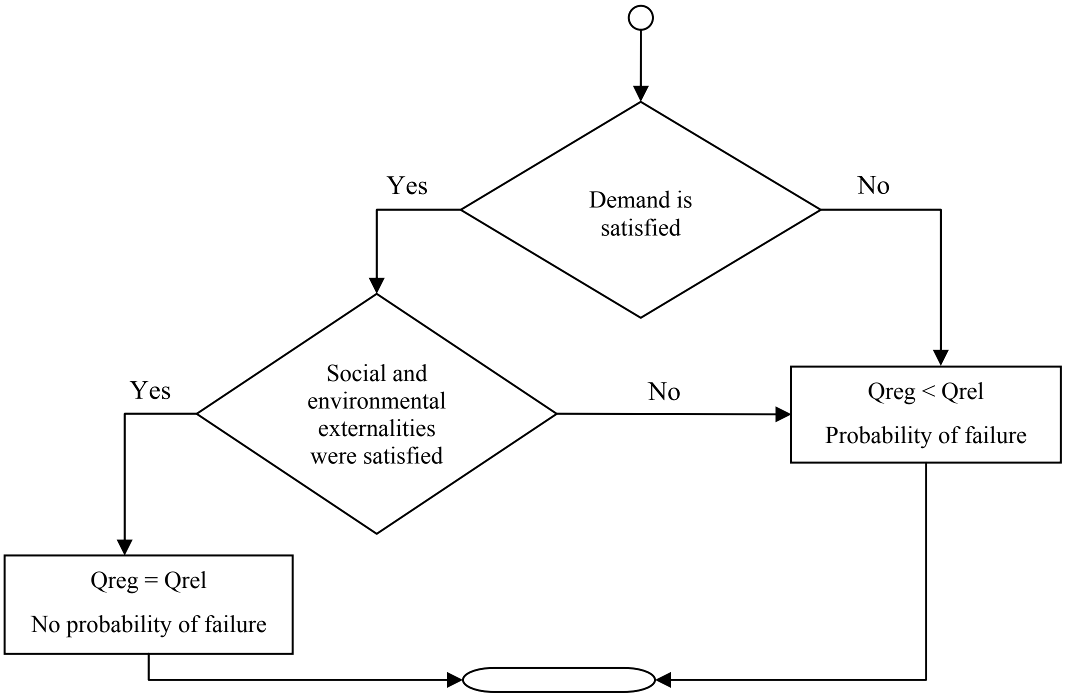


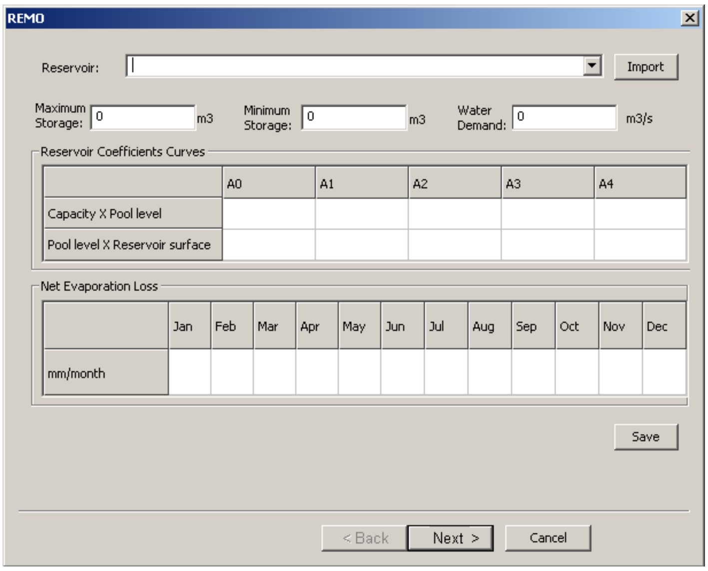
Figure 2: System Architecture

5 REMO SIMULATION

When the user first starts REMO, he will see the main window shown in Figure 3. He must enter the following information: reservoir name; maximum and minimum storage capacity;

water demand; capacity pool level and pool level reservoir surface coefficients curves; and net evaporation loss.

The system allows saving the reservoir data for future simulations, by selecting Save button. To recover the information from the data base, the user must type the reservoir name and select Import button (Figure 4).



Reservoir:

Maximum Storage: 0 m3

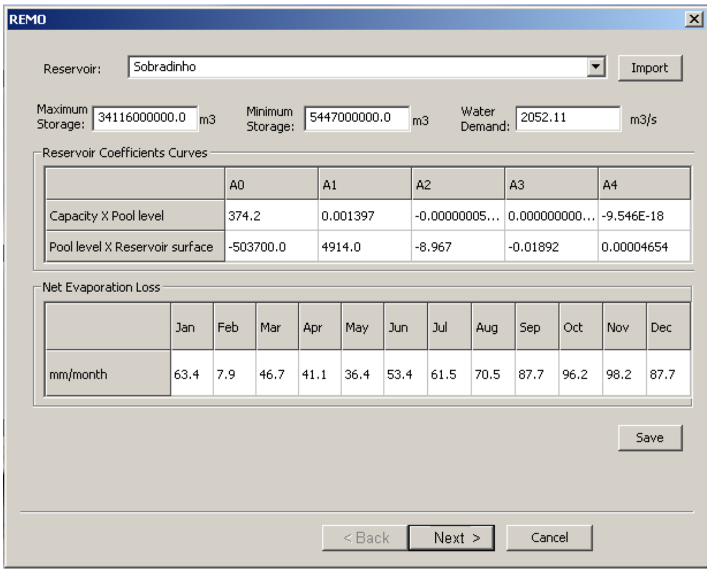
Minimum Storage: 0 m3

Water Demand: 0 m3/s

	A0	A1	A2	A3	A4
Capacity X Pool level					
Pool level X Reservoir surface					

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mm/month												

Figure 3: First Window



Reservoir: Sobradinho

Maximum Storage: 34116000000.0 m3

Minimum Storage: 5447000000.0 m3

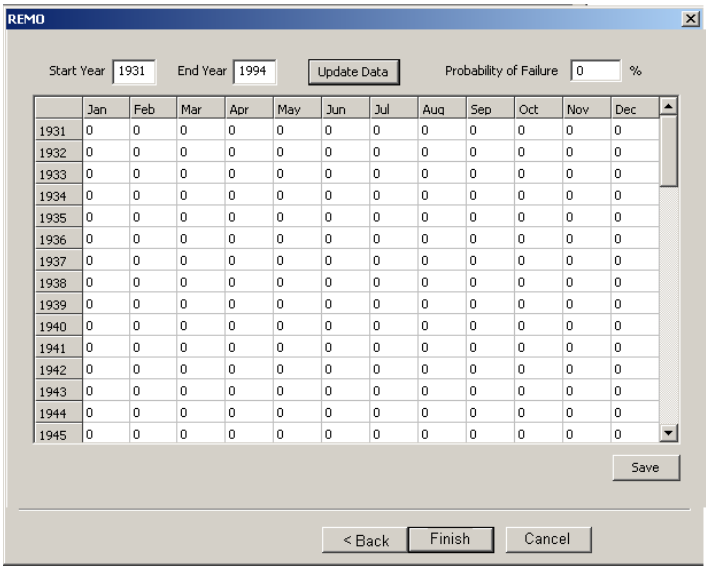
Water Demand: 2052.11 m3/s

	A0	A1	A2	A3	A4
Capacity X Pool level	374.2	0.001397	-0.00000005...	0.000000000...	-9.546E-18
Pool level X Reservoir surface	-503700.0	4914.0	-8.967	-0.01892	0.00004654

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mm/month	63.4	7.9	46.7	41.1	36.4	53.4	61.5	70.5	87.7	96.2	98.2	87.7

Figure 4: Reservoir Imported Data

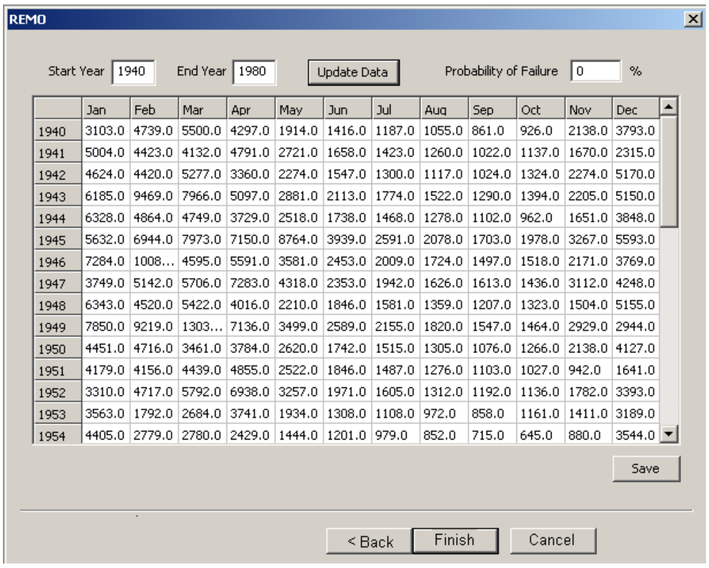
The user should select Next > button to move to the next window. The historical inflow record is required to perform the calculations, as the start and end date and the probability of failure, as illustrated in Figure 5. After entering the start and end year, the user must press Update Data button, then he will be allowed to enter and edit the historical record and save by pressing the Save button. If he is interested to simulate another period, he may edit the start and end year and press Update Data button (Figure 6). The user can change any data from the historical record and save the modifications by pressing Save button.



Start Year 1931
End Year 1994
Probability of Failure 0 %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1931	0	0	0	0	0	0	0	0	0	0	0	0
1932	0	0	0	0	0	0	0	0	0	0	0	0
1933	0	0	0	0	0	0	0	0	0	0	0	0
1934	0	0	0	0	0	0	0	0	0	0	0	0
1935	0	0	0	0	0	0	0	0	0	0	0	0
1936	0	0	0	0	0	0	0	0	0	0	0	0
1937	0	0	0	0	0	0	0	0	0	0	0	0
1938	0	0	0	0	0	0	0	0	0	0	0	0
1939	0	0	0	0	0	0	0	0	0	0	0	0
1940	0	0	0	0	0	0	0	0	0	0	0	0
1941	0	0	0	0	0	0	0	0	0	0	0	0
1942	0	0	0	0	0	0	0	0	0	0	0	0
1943	0	0	0	0	0	0	0	0	0	0	0	0
1944	0	0	0	0	0	0	0	0	0	0	0	0
1945	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5: Historical Record Editor



Start Year 1940
End Year 1980
Probability of Failure 0 %

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1940	3103.0	4739.0	5500.0	4297.0	1914.0	1416.0	1187.0	1055.0	861.0	926.0	2138.0	3793.0
1941	5004.0	4423.0	4132.0	4791.0	2721.0	1658.0	1423.0	1260.0	1022.0	1137.0	1670.0	2315.0
1942	4624.0	4420.0	5277.0	3360.0	2274.0	1547.0	1300.0	1117.0	1024.0	1324.0	2274.0	5170.0
1943	6185.0	9469.0	7966.0	5097.0	2881.0	2113.0	1774.0	1522.0	1290.0	1394.0	2205.0	5150.0
1944	6328.0	4864.0	4749.0	3729.0	2518.0	1738.0	1468.0	1278.0	1102.0	962.0	1651.0	3848.0
1945	5632.0	6944.0	7973.0	7150.0	8764.0	3939.0	2591.0	2078.0	1703.0	1978.0	3267.0	5593.0
1946	7284.0	1008...	4595.0	5591.0	3581.0	2453.0	2009.0	1724.0	1497.0	1518.0	2171.0	3769.0
1947	3749.0	5142.0	5706.0	7283.0	4318.0	2353.0	1942.0	1626.0	1613.0	1436.0	3112.0	4248.0
1948	6343.0	4520.0	5422.0	4016.0	2210.0	1846.0	1581.0	1359.0	1207.0	1323.0	1504.0	5155.0
1949	7850.0	9219.0	1303...	7136.0	3499.0	2589.0	2155.0	1820.0	1547.0	1464.0	2929.0	2944.0
1950	4451.0	4716.0	3461.0	3784.0	2620.0	1742.0	1515.0	1305.0	1076.0	1266.0	2138.0	4127.0
1951	4179.0	4156.0	4439.0	4855.0	2522.0	1846.0	1487.0	1276.0	1103.0	1027.0	942.0	1641.0
1952	3310.0	4717.0	5792.0	6938.0	3257.0	1971.0	1605.0	1312.0	1192.0	1136.0	1782.0	3393.0
1953	3563.0	1792.0	2684.0	3741.0	1934.0	1308.0	1108.0	972.0	858.0	1161.0	1411.0	3189.0
1954	4405.0	2779.0	2780.0	2429.0	1444.0	1201.0	979.0	852.0	715.0	645.0	880.0	3544.0

Figure 6: Historical Record Example

Once all data have been entered, the user must select Finish button to initiate the simulation. It is recommended start the system performance by typing zero in the probability failure box (Figure 5 and Figure 6). If simulation process can reach a result, it means demand is equal to regulated discharge (no probability of failure) and the system will present the window shown in Figure 7. The user must type the file name and the output will be generated in HTML format. Sobradinho simulation partial results can be viewed in Table 1, which also presents the critical period (April, 1953 to March, 1957).

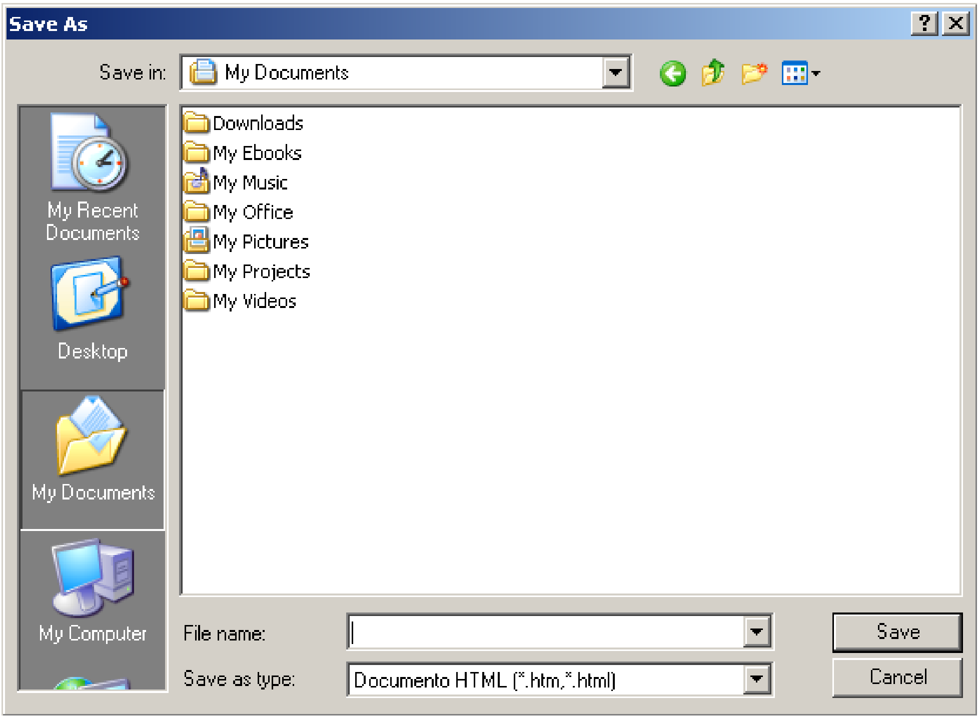
São Francisco
Sobradinho
Time period: 768 month(s)
Total Storage Capacity: 34,044,020,736.00 m³
Dead Storage: 5,447,000,064.00 m³
Demand: 2,052.11 m³/s
Regulated Discharge: 2,052.11 m³/s
Average Discharge: 2,792.82 m³/s

Month	Year	Qinf (m³/s)	Qevap (m³/s)	Qrel (m³/s)	Qspill (m³/s)	NA (m)	S (%)	Demand Failure
1	1951	4175	93.36	2052.11	0	393.84	99.48	No
2		4152	13.23	4138.77	2086.66	393.88	100.00	No
3		4435	83.22	4351.78	2299.67	393.88	100.00	No
4		4851	73.37	4777.63	2725.52	393.88	100.00	No
5		2518	64.98	2453.02	400.91	393.88	100.00	No
6		1842	95.33	2052.11	0	393.69	97.64	No
7		1483	108.88	2052.11	0	393.26	92.40	No
8		1272	121.37	2052.11	0	392.65	85.44	No
9		1099	143.93	2052.11	0	391.87	76.97	No
10		1023	147.99	2052.11	0	391.02	67.87	No
11		938	139.75	2052.11	0	390.08	58.19	No
12		1638	114.28	2052.11	0	389.67	54.11	No
1	1952	3306	77.19	2052.11	0	390.57	63.19	No
2		4714	9.86	2052.11	0	392.49	83.68	No
3		5788	67.00	5721.00	3668.89	393.88	100.00	No
4		6934	68.90	6865.10	4812.99	393.88	100.00	No
5		3253	64.98	3188.02	1135.91	393.88	100.00	No
6		1967	95.33	2052.11	0	393.77	98.61	No
7		1600	109.26	2052.11	0	393.42	94.27	No
8		1307	122.67	2052.11	0	392.84	87.57	No
9		1188	146.26	2052.11	0	392.13	79.76	No
10		1132	151.15	2052.11	0	391.36	71.49	No
11		1778	143.85	2052.11	0	391.06	68.26	No
12		3389	121.95	2052.11	0	391.94	77.64	No
1	1953	3559	90.66	2052.11	0	392.93	88.58	No
2		1789	12.35	2052.11	0	392.74	86.45	No
3		2681	75.80	2052.11	0	393.12	90.73	No
4		3736	67.29	3668.71	1616.6	393.88	100.00	No
5		1930	62.79	2052.11	0	393.77	98.57	No
6		1303	94.86	2052.11	0	393.23	92.05	No
7		1103	106.09	2052.11	0	392.51	83.90	No
8		967	114.81	2052.11	0	391.66	74.63	No
9		852	132.66	2052.11	0	390.68	64.34	No
10		1156	133.25	2052.11	0	389.90	56.39	No
11		1407	124.69	2052.11	0	389.30	50.44	No
12		3185	103.76	2052.11	0	390.10	58.39	No
1	1954	4401	75.78	2052.11	0	391.78	75.95	No
2		2775	10.70	2052.11	0	392.29	81.45	No
3		2776	70.31	2052.11	0	392.74	86.50	No
4		2425	64.76	2052.11	0	392.95	88.88	No
5		1439	59.16	2052.11	0	392.49	83.69	No
6		1195	85.78	2052.11	0	391.82	76.40	No
7		974	93.67	2052.11	0	390.97	67.35	No
8		847	99.83	2052.11	0	389.99	57.27	No
9		710	113.48	2052.11	0	388.82	46.03	No
10		640	111.57	2052.11	0	387.41	34.26	No
11		876	99.33	2052.11	0	385.96	24.40	No
12		3540	75.74	2052.11	0	387.55	35.31	No

Table 1: Simulation output without failure.

1	1955	2306	55.18	2052.11	0	387.74	36.85	No
2		4047	7.59	2052.11	0	389.48	52.20	No
3		2161	49.82	2052.11	0	389.53	52.65	No
4		2611	48.14	2052.11	0	389.93	56.60	No
5		1432	43.63	2052.11	0	389.40	51.47	No
6		1067	63.60	2052.11	0	388.52	43.37	No
7		894	68.10	2052.11	0	387.36	33.90	No
8		782	69.99	2052.11	0	385.81	23.55	No
9		671	74.93	2052.11	0	383.64	12.30	No
10		655	66.30	2052.11	0	380.70	1.00	No
11		1973	49.79	2052.11	0	380.40	0	No
12		3301	36.62	2052.11	0	382.96	9.36	No
1	1956	5366	30.29	2052.11	0	387.47	34.73	No
2		2211	5.77	2052.11	0	387.62	35.91	No
3		4581	44.40	2052.11	0	389.78	55.10	No
4		2538	44.26	2052.11	0	390.12	58.52	No
5		1768	44.62	2052.11	0	389.86	55.98	No
6		1634	65.75	2052.11	0	389.48	52.24	No
7		1320	73.31	2052.11	0	388.82	46.02	No
8		1061	79.62	2052.11	0	387.85	37.75	No
9		897	90.87	2052.11	0	386.54	28.12	No
10		835	88.01	2052.11	0	384.83	18.04	No
11		1464	75.68	2052.11	0	383.78	12.91	No
12		3683	57.47	2052.11	0	386.06	25.07	No
1	1957	5944	44.70	2052.11	0	389.74	54.78	No
2		7114	7.81	2052.11	0	393.38	93.83	No
3		6899	67.20	6831.8	4779.69	393.88	100.00	No
4		7959	71.75	7887.25	5835.14	393.88	100.00	No
5		5810	64.98	5745.02	3692.91	393.88	100.00	No
6		2762	95.33	2666.67	614.56	393.88	100.00	No
7		2027	109.79	2052.11	0	393.80	98.96	No
8		1638	125.40	2052.11	0	393.46	94.79	No
9		1366	153.09	2052.11	0	392.90	88.31	No
10		1516	161.23	2052.11	0	392.42	82.92	No
11		1411	156.87	2052.11	0	391.85	76.76	No
12		4338	133.35	2052.11	0	393.34	93.38	No
1	1958	3619	100.68	3518.32	1466.21	393.88	100.00	No
2		5208	13.77	5194.23	3142.12	393.88	100.00	No
3		3381	83.37	3297.63	1245.52	393.88	100.00	No
4		3099	73.37	3025.63	973.52	393.88	100.00	No
5		2415	64.98	2350.02	297.91	393.88	100.00	No
6		1691	95.33	2052.11	0	393.60	96.47	No
7		1406	108.42	2052.11	0	393.11	90.65	No
8		1414	120.03	2052.11	0	392.59	84.79	No
9		1121	142.55	2052.11	0	391.83	76.50	No
10		1512	147.28	2052.11	0	391.33	71.19	No
11		1833	141.58	2052.11	0	391.07	68.40	No
12		1794	121.86	2052.11	0	390.79	65.46	No
1	1959	3597	85.78	2052.11	0	391.85	76.74	No
2		3655	11.11	2052.11	0	392.97	89.03	No
3		3490	72.86	2052.11	0	393.85	99.58	No
4		2702	70.31	2631.69	579.58	393.88	100.00	No
5		1357	64.89	2052.11	0	393.41	94.13	No
6		1132	93.32	2052.11	0	392.73	86.30	No
7		1008	101.98	2052.11	0	391.92	77.45	No
8		898	109.08	2052.11	0	391.00	67.69	No
9		813	124.97	2052.11	0	389.98	57.15	No
10		841	124.61	2052.11	0	388.91	46.83	No
11		1595	114.35	2052.11	0	388.41	42.42	No
12		2707	94.07	2052.11	0	388.90	46.75	No

Table 1: Simulation output without failure (Continuation).



Save in: My Documents

File name:

Save as type: Documento HTML (*.htm,*.html)

Figure 7: Simulation Output Window

If the system cannot reach a result, a message will appear (Figure 8). It means demand is above regulated discharge, so the user must type different values of probability of failure until the application is able to generate a result by presenting the window shown in Figure 7. The user must type the file name and the output will be generated in HTML format (Table 2).

Maximum storage insuficient to meet the demand.

Figure 8: System Message

6 METHODOLOGY AND SOFTWARE VALIDATION

To evaluate the methodology and software in order determine whether it satisfies the specified requirements and the accurate representation from the perspective of the intended use, two test cases were executed, both with hydropower reservoirs, Sobradinho and Boa Esperança.

Sobradinho hydroelectric power plant is located on the lower middle São Francisco River at 40º50’W and 9º35’S, Bahia State, Brazil. It has capacity for 34.116 billion m^3 of water, with 1,500 MW power generation. The lake is 320 km long with 4,214 km^2 of surface area and it is considered one of the largest artificial reservoirs in the world. According to CHESF (2010), proprietor of the power plant, it has an active storage capacity of 28.669 billion m^3; maximum and minimum pool level of 393.5 m and 380.5 m, respectively; and regulated discharge of 2,060 m^3/s. The historical inflow record, from January, 1931 to December, 1994, was obtained from SIPOT database (Brazilian Hydroelectric Potential Information System). Table 3 illustrates more detailed information.

São Francisco
Sobradinho
Time period: 768 month(s)

Total Storage Capacity:	34,044,020,736.00	m³
Dead Storage:	5,447,000,064.00	m³
Active Storage with Pe = 10%:	13,060,643,840.00	m³
Demand:	2,052.11	m³/s
Regulated Discharge:	1,564.11	m³/s
Average Discharge:	2,792.82	m³/s

Month	Year	Qinf (m³/s)	Qevap (m³/s)	Qrel (m³/s)	Qspill (m³/s)	NA (m)	S (%)	Demand Failure
1	1951	4175	43.19	4131.81	2079.70	387.93	100	No
2		4152	7.10	4144.90	2092.79	387.93	100	No
3		4435	46.31	4388.69	2336.58	387.93	100	No
4		4851	40.76	4810.24	2758.13	387.93	100	No
5		2518	36.10	2481.90	429.79	387.93	100	No
6		1842	52.95	2052.11	0	387.68	94.70	No
7		1483	60.15	2052.11	0	387.03	82.03	No
8		1272	65.61	2052.11	0	386.04	65.00	No
9		1099	74.50	2052.11	0	384.63	44.31	No
10		1023	71.19	2052.11	0	382.75	22.16	No
11		**938**	**59.80**	**878.20**	**0**	**380.40**	**0**	**Yes**
12		**1638**	**41.37**	**1596.63**	**0**	**380.40**	**0**	**Yes**
1	1952	3306	26.01	2052.11	0	382.99	24.72	No
2		4714	3.78	2052.11	0	386.82	78.25	No
3		5788	32.87	5755.13	3703.02	387.93	100	No
4		6934	38.35	6895.65	4843.54	387.93	100	No
5		3253	36.10	3216.90	1164.79	387.93	100	No
6		1967	52.95	2052.11	0	387.80	97.22	No
7		1600	60.55	2052.11	0	387.28	86.90	No
8		1307	66.99	2052.11	0	386.38	70.55	No
9		1188	77.02	2052.11	0	385.16	51.60	No
10		1132	74.86	2052.11	0	383.60	31.56	No
11		1778	64.93	2052.11	0	382.99	24.73	No
12		3389	50.93	2052.11	0	385.09	50.63	No
1	1953	3559	40.27	2052.11	0	386.93	80.16	No
2		1789	6.32	2052.11	0	386.62	74.73	No
3		2681	40.75	2052.11	0	387.27	86.58	No
4		3736	36.56	3699.44	1647.33	387.93	100	No
5		1930	34.81	2052.11	0	387.78	96.84	No
6		1303	52.52	2052.11	0	386.95	80.70	No
7		1103	57.34	2052.11	0	385.75	60.43	No
8		967	58.67	2052.11	0	384.09	37.40	No
9		852	61.82	2052.11	0	381.74	11.99	No
10		**1156**	**53.34**	**1102.66**	**0**	**380.40**	**0**	**Yes**
11		**1407**	**43.60**	**1363.40**	**0**	**380.40**	**0**	**Yes**
12		3185	35.97	2052.11	0	382.75	22.09	No
1	1954	4401	29.90	2052.11	0	386.27	68.78	No
2		2775	5.31	2052.11	0	387.09	83.23	No
3		2776	40.33	2052.11	0	387.79	96.99	No
4		2425	38.62	2386.38	334.27	387.93	100	No
5		1439	35.82	2052.11	0	387.29	86.93	No
6		1195	51.12	2052.11	0	386.27	68.65	No
7		974	53.68	2052.11	0	384.74	45.86	No
8		847	53.21	2052.11	0	382.6	20.52	No
9		**710**	**53.27**	**656.73**	**0**	**380.40**	**0**	**Yes**
10		**640**	**44.96**	**595.04**	**0**	**380.40**	**0**	**Yes**
11		**876**	**40.28**	**835.72**	**0**	**380.40**	**0**	**Yes**
12		3540	35.97	2052.11	0	383.40	29.23	No

Table 2: Simulation output with failure.

1	1955	2306	31.09	2052.11	0	383.78	33.72	No
2		4047	4.75	2052.11	0	386.57	73.79	No
3		2161	33.92	2052.11	0	386.65	75.30	No
4		2611	35.22	2052.11	0	387.23	85.85	No
5		1432	32.37	2052.11	0	386.51	72.71	No
6		1067	47.09	2052.11	0	385.18	51.93	No
7		894	48.27	2052.11	0	383.26	27.63	No
8		782	45.73	2052.11	0	380.53	1.14	No
9		**671**	**42.99**	**628.01**	**0**	**380.40**	**0**	**Yes**
10		**655**	**39.77**	**615.23**	**0**	**380.40**	**0**	**Yes**
11		**1973**	**40.28**	**1932.72**	**0**	**380.40**	**0**	**Yes**
12		3301	35.97	2052.11	0	382.96	24.42	No
1	1956	5366	30.29	2052.11	0	387.47	90.54	No
2		2211	5.77	2052.11	0	387.62	93.62	No
3		4581	44.40	4536.60	2484.49	387.93	100	No
4		2538	40.08	2497.92	445.81	387.93	100	No
5		1768	36.10	2052.11	0	387.62	93.55	No
6		1634	52.06	2052.11	0	387.14	84.09	No
7		1320	57.40	2052.11	0	386.24	68.19	No
8		1061	60.92	2052.11	0	384.83	47.01	No
9		897	66.41	2052.11	0	382.78	22.41	No
10		**835**	**59.37**	**775.63**	**0**	**380.40**	**0**	**Yes**
11		**1464**	**46.39**	**1417.61**	**0**	**380.40**	**0**	**Yes**
12		3683	35.97	2052.11	0	383.65	32.11	No
1	1957	5944	31.56	5912.44	3860.33	387.93	100	No
2		7114	6.16	7107.84	5055.73	387.93	100	No
3		6899	46.31	6852.69	4800.58	387.93	100	No
4		7959	40.76	7918.24	5866.13	387.93	100	No
5		5810	36.10	5773.90	3721.79	387.93	100	No
6		2762	52.95	2709.05	656.94	387.93	100	No
7		2027	60.99	2052.11	0	387.85	98.27	No
8		1638	69.60	2052.11	0	387.37	88.53	No
9		1366	83.95	2052.11	0	386.52	73.02	No
10		1516	85.58	2052.11	0	385.76	60.50	No
11		1411	79.76	2052.11	0	384.75	45.99	No
12		4338	64.30	2052.11	0	387.48	90.72	No
1	1958	3619	51.34	3567.66	1515.55	387.93	100	No
2		5208	7.64	5200.36	3148.25	387.93	100	No
3		3381	46.31	3334.69	1282.58	387.93	100	No
4		3099	40.76	3058.24	1006.13	387.93	100	No
5		2415	36.10	2378.90	326.79	387.93	100	No
6		1691	52.95	2052.11	0	387.53	91.66	No
7		1406	59.66	2052.11	0	386.78	77.45	No
8		1414	64.17	2052.11	0	385.94	63.31	No
9		1121	73.00	2052.11	0	384.53	43.09	No
10		1512	70.37	2052.11	0	383.53	30.80	No
11		1833	62.31	2052.11	0	383.03	25.13	No
12		1794	50.84	2052.11	0	382.44	18.91	No
1	1959	3597	34.41	2052.11	0	385.00	49.33	No
2		3655	4.83	2052.11	0	387.00	81.51	No
3		3490	37.31	3452.69	1400.58	387.93	100	No
4		2702	38.73	2663.27	611.16	387.93	100	No
5		1357	36.10	2052.11	0	387.20	85.28	No
6		1132	50.88	2052.11	0	386.09	65.73	No
7		1008	52.88	2052.11	0	384.58	43.64	No
8		898	52.15	2052.11	0	382.48	19.35	No
9		**813**	**52.38**	**760.62**	**0**	**380.40**	**0**	**Yes**
10		**841**	**44.65**	**796.35**	**0**	**380.40**	**0**	**Yes**
11		**1595**	**40.28**	**1554.72**	**0**	**380.40**	**0**	**Yes**
12		2707	35.97	2052.11	0	381.79	12.46	No

Table 2: Simulation output with failure (Continuation).

Reservoir Coefficients Curves			**A0**		**A1**		**A2**		**A3**		**A4**	
Capacity x Pool Level			$3.742E^{+02}$		$1.397E^{-03}$		$-5.352E^{-08}$		$1.156E^{-12}$		$-9.546E^{-18}$	
Pool Level x Reservoir Surface			$-5.037E^{+05}$		$4.914\ E^{+03}$		$-8.967\ E^{00}$		$-1.892E^{-02}$		$4.654E^{-05}$	
Net Evaporation	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	63.4	7.9	46.7	41.1	36.4	53.4	61.5	70.5	87.7	96.2	98.2	87.7

Table 3: Hydraulic and hydrological information of Sobradinho Reservoir.

Boa Esperança hydroelectric power plant is located on Parnaiba River at 43º30’W and 6º50’S, Piaui State, Brazil. According to CHESF (2010), proprietor of the power plant, it has a total capacity of 5.085 billion m^3; active storage capacity of 1.917 billion m^3; maximum and minimum pool level of 306.5 m and 298.0 m, respectively; and regulated discharge of 352 m^3/s. The historical inflow record, from January, 1931 to December, 1994, was obtained from SIPOT database (Brazilian Hydroelectric Potential Information System). Table 4 illustrates more detailed information.

Reservoir Coefficients Curves			**A0**		**A1**		**A2**		**A3**		**A4**	
Capacity x Pool Level			$2.820E^{+02}$		$6.681E^{-03}$		$-6.286E^{-07}$		$3.690E^{-11}$		$-7.799E^{-16}$	
Pool Level x Reservoir Surface			$-5.406E^{+02}$		$-1.126E^{+01}$		$1.492E^{-01}$		$-6.703E^{-04}$		$1.097E^{-06}$	
Net Evaporation	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	24.3	7.9	17.6	15.8	22.3	36.8	53.2	75.4	93.1	95.4	76.8	53.2

Table 4: Hydraulic and hydrological information of Boa Esperança Reservoir.

The regulated discharges and the active storage capacity estimated by REMO were compared with the values published by São Francisco Hydroelectric Company (CHESF), and the differences are presented Table 5.

Reservoir	**Qreg (m^3/s)**		**Difference (%)**	**C (m^3)**		**Difference (%)**
	REMO	**CHESF**		**REMO**	**CHESF**	
Sobradinho	2,052.11	2,060	-0.38	28,497,020,672	28,669,000,000	-0.60
Boa Esperança	352.11	352	0.03	1,862,526,720	1,917,000,000	-2,84

Table 5: Comparison between the results achieved in REMO (simulation without failure) and CHESF (2010).

7 CONCLUSIONS

The simulation for Sobradinho and Boa Esperança reservoirs shows a difference between CHESF (2010) and REMO of 0,4% for the regulated discharge and 2,8% for the active storage capacity. Thus, the system is suitable to the proposed objectives.

The adoption of failures in the estimation of the demand in a reservoir is a useful procedure which balances conflicts among the social-environmental impacts (inundation areas interfering in wildlife or villages) and the need of water supply. This procedure, allied with other alternatives to decrease the water deficit, tends to be the solution that brings more benefit for all stakeholders and, in the aspect of the water resources management, the most balanced.

REMO proved to be an excellent tool to help the water manager during the decision process to choose the best alternative to increase the water availability in basins with scarcity or where the future requirements may cause a water stress. This can enable the Government Agencies to take decisions based on a scientific basis and thus ensuring timely release of water for multiple uses.

As future studies, it is recommended the application of REMO in other Brazilian river basins.

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