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São Francisco river Integration Project, Eastern Axis: losses analysis and performance indicators

Projeto de Integração do Rio São Francisco, Eixo Leste: analise de perdas e indicadores de desempenho

Emmanuel Eduardo Vitorino de Farias[1], Wilson Fadlo Curi[1] and Laudízio da Silva Diniz[2]

[1]Universidade Federal de Campina Grande, Campina Grande, PB, Brazil
[2]Companhia de Água e Esgotos da Paraíba, João Pessoa, PB, Brazil
E-mails: eduboavista@gmail.com (EEVF), wfcuri@gmail.com (WFC), laudizio@terra.com.br (LSD)

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ABSTRACT

Water scarcity is an old problem in the brazilian Northeast semiarid region and limits the economic and social development of the region. To mitigate negative impacts of this situation, the National Integration Ministry elaborated the São Francisco River Integration Project (PISF). The State of Paraíba will benefit from this project through the East Axis and West Axis water transposition systems' from the São Francisco river. The Paraíba riverbasin will receive the waters of the São Francisco river through the Eastern Axis, since the project foresees that, from the city of Monteiro-PB, the water will be transported through the bed of the Paraíba river. This type of transport will cause high water losses. The present work analyzes water distribution scenarios in terms of water losses, which were simulated with the Acquanet model. The first scenario simulates the current situation, without water transposition of PISF, and the other ones evaluate different ways of distributing the waters of the East Axis among the Paraíba river bed and different pipelines construction scenarios. The results have shown that the construction of pipelines will reduce water losses and increase social gain, through the increase of the benefited population.

Keywords: São Francisco; AcquaNet; Losses analysis.

RESUMO

A escassez hídrica é um problema antigo no semiárido nordestino brasileiro e limita o desenvolvimento econômico e social da região. Para mitigar impactos negativos desta situação o Ministério da Integração Nacional elaborou o Projeto de Integração do Rio São Francisco – PISF. O estado da Paraíba será beneficiado com este projeto pelos sistemas de transposição de águas do rio São Francisco através do Eixo Leste e do Eixo Oeste. A bacia hidrográfica do Rio Paraíba receberá as águas do rio São Francisco através do Eixo Leste, sendo que o projeto prevê que, a partir da cidade de Monteiro-PB, as águas serão transportadas através do leito do rio Paraíba. Esse tipo de transporte acarretará elevadas perdas hídricas. O presente trabalho analisa o desempenho de cenários de distribuição destas águas em termos de perdas hídricas, que foram simuladas com o modelo AcquaNet. O primeiro cenário a situação atual, sem a transposição das águas do PISF e os demais avaliam diferentes formas de distribuir as águas do Eixo Leste entre o leito do rio Paraíba e diferentes cenários de construção de adutoras. Os resultados demonstram que a construção de adutoras reduzirá perdas hídricas e aumentará o ganho social, através do aumento da população beneficiada.

Palavras-chave: São Francisco; AcquaNet; Analises de perdas.

INTRODUCTION

Water scarcity is a reality in the northeast of the semi-arid region, where many cities are on the edge of a water collapse and operate under a rationing system. This problem is aggravated by population growth and industrial and agricultural activities, together with a decrease in the availability of drinking water, caused by pollution, deforestation and climate change. These factors limit the economic and social development of this region, since water is an indispensable resource in practically all economic activities.

Within this context, with prolonged droughts, the reservoirs of the Paraíba river basin are generally in critical condition. Its main reservoir, the Epitacio Pessoa, also known as Boqueirão, which is responsible for supplying 17 cities, including Campina Grande, with an estimated population of 407,754 inhabitants (IBGE, 2016), has already operated in its dead storage volume, with about 3.6% of its capacity in 2017, reaching the lowest volume in its history. The other reservoirs in this basin have already reached the following volumes: Camalaú 6%, Poções 0.8%, Acauã 6% (AESA, 2007). This demonstrates that this basin shows great water vulnerability and can lead to a total collapse in the water supply if the rains are not enough to recover the water stocks in its main reservoirs. In this chaotic scenario, the only way to guarantee the water supply of these cities is the exogenous flow coming from the Integration Project of the São Francisco River - PISF. Because it is a water that involves high costs of transposition, it is necessary to make a good use of this resource, in particular, minimizing water losses.

However, in its original conception, the Ministry of National Integration together with the state government intend to transport the PISF water through the Paraíba river bed. Such a procedure will significantly increase the water losses, during its transit, through infiltration and evaporation processes, reducing the water availability to the final consumer of the PISF. Since the lost water has a relatively high fixed cost, a feasible solution to reduce losses is to make use of pipelines to transport part of this flow from dams belonging to the Paraíba river basin, in order to supply the largest possible number of cities, widening the project range reach and improving the rational use of water, guaranteeing social and economic gains.

In this work, seven PISF water distribution scenarios in the Paraíba river basin simulations were performed, using the mathematical model AcquaNet (USP, 2002), which is based on flow network. For each scenario, the operational policy and the quantification of its water losses related to infiltration, evaporation and reservoir spilling, resulting from PISF directives, were evaluated in a system composed of four reservoirs in a row in the Paraíba River.

MATERIAL AND METHODS

Study field

The Paraíba River Basin has an coverage area of 20,071.83 km^2 (PARAÍBA, 2004). Due to its great geographic extent and climatic and physical diversities, the Paraíba River basin was divided into a sub-basin of the Taperoá River, which is an affluent river to the system, and in three hydrographic regions: Alto Paraíba, Médio Paraíba and Baixo Paraíba. Its area includes 71 municipalities that hold a population of 1,866,521 inhabitants, corresponding to 52% of the population of the State. This basin has, along the Paraíba River, four reservoirs in a row: Poções with a capacity of 30 hm^3, Camalaú with a capacity of 46 hm^3, Epitácio Pessoa, known as Boqueirão, with a capacity of 412 hm^3, and Argemiro Figueiredo, known as Acauã, with a capacity of 253 hm^3.

From the Epitácio Pessoa dam two water supply systems are derived: the Gravatá system with 60 km pipeline extension, which supplies the municipalities of Campina Grande, Queimadas, Galante, Caturité, Pocinhos, Riacho de Santo Antonio, Barra de Santana, Barra de São Miguel; and the Cariri water supply system with 160 km of pipeline extension, which serves the municipalities of Boqueirão, Cabaceiras, Boa Vista, Soledade, Seridó, São Vicente do Seridó, Olivedos, Juazeirinho, Cubatí and Pedra Lavrada. According to data from AESA (2016), the reservoir has already operated in its dead storage volume, with an imminent risk of water collapse. In this case, the supply would be guaranteed by the exogenous PISF flow.

The Acauã dam was completed in 2002. This reservoir was designed to supply the cities of Itabaiana, Salgado de São Felix, Natuba and Itatuba, and to reinforce the integrated supply system of Campina Grande and to control floods in the lower course of the Paraíba River.

According to AESA (2007), the Paraíba River basin will receive from the PISF a continuous flow of 4,200 L.s^{-1}, which may reach 10,000 L.s^{-1}. The maximum value should be reached if the catchment basin is in recurrent periods of scarcity and the Sobradinho reservoir, located in the São Francisco river with a capacity of 28,669 hm^3, is spilling.

Figure 1 shows the Paraíba river basin, with its main reservoirs.

Methodology

General description

In order to quantify the water losses of the PISF, in the Paraíba river basin, the AcquaNet simulation model was used, since it allows a system composed of several reservoirs, with their respective demands, be represented in a simple way and with the necessary detail to this type of analysis. AcquaNet is a mathematical model based on the theory of the network flow model. In the simulation it uses mass balance algorithm and in the optimization, is used the algorithm "Out-of-kilter", and the primal-dual linear programming. Through network flow method it is possible to represent complete river basins through arcs (links) and nodes. The layout of the system that will receive the exogenous PISF East Axis flow is shown in Figure 2. The delivery point will be the Poções reservoir, located in the municipality of Monteiro, from which the waters will pass through the reservoirs of Camalaú, Boqueirão and Acauã, and three irrigated perimeters are planned: Poções, Congo and Vereda Grande. From Acauã, there should be a regular flow to supply the municipalities on the banks of the Paraíba River to the ocean and meet the demands of the downstream Acauã-Araçagi Channel, also called the Integration Channel.

Figure 1. Paraiba river basin with its main reservoirs. Source: AESA (2007).

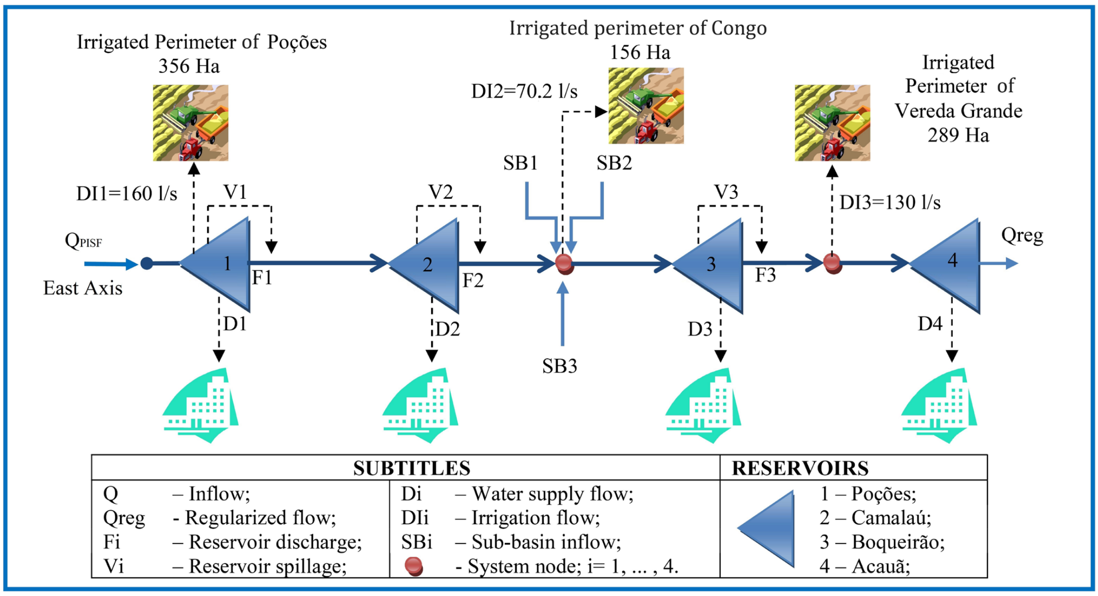

Figure 2. Layout of the system, which will receive water from the East Axis of PISF.

Input data

For the present study the input data were:

1. Month average of precipitations and evaporations data, for each simulated reservoir;
2. Curves quota x area x volume for the reservoirs under study;
3. Series of fluviometric data, in monthly scale for the simulated period;
4. Percentage of losses in transit for each section of the studied river;
5. Requests for water supply and irrigation on a monthly basis;
6. System priorities with values ranging from 1 to 99 (the lower the value the higher the priority.

Data from items 1 to 5 were provided by AESA (2007).

a) Climatic and fluviometric data

For reservoirs, the input data are precipitation, evaporation and curves quota x area x volume. Precipitation and evaporation data were obtained from the monthly averages of the pluviometric stations closest to the reservoirs under study, as presented in Table 1. All these data were made available by the AESA.

According to AESA (2007), the water losses in transit along the Paraíba river bed due to infiltration and evaporation is of the order of 14% between Poções and Boqueirão reservoirs (Alto Paraíba) and 22% for the section between Boqueirão and Acauã (Médio Paraíba).

Fluviometric data were provided by AESA (2007). This series of data, is in monthly scale that goes from January 1933 to December 1991, totaling of 59 years.

Table 1. Month average of precipitation and evaporation.

Reservoirs	Average (mm)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Poções	Precipitation	32.8	70.2	128	96.1	55.1	31.5	18.2	7.9	3.7	8.6	11.8	15.5
	Evaporation	233	178	156	116	115	127	156	206	239	263	266	273
Camalaú	Precipitation	50.5	83.8	144	139	65.7	36.5	34.1	17	10.1	6.5	14.3	23.4
	Evaporation	233	178	156	116	115	127	156	206	239	263	266	273
Boqueirão	Precipitation	27.5	54.2	81.5	98.4	57.4	56.2	5.5	20.7	12.2	4.6	6.8	16
	Evaporation	192	155	195	163	178	130	109	143	166	237	212	228
Acauã	Precipitation	35.7	48.7	92.6	108	74.6	74.3	88.8	39.3	22.5	9.9	9.8	25.5
	Evaporation	147	132	108	88	102	65	73	105	126	154	151	165

b) Demand data

b.1) Irrigation demand

Based on PDRH-PB (PARAÍBA, 2001), the estimated irrigation water demand was 0.45 $l.s^{-1}.ha^{-1}$, which is assumed not to have changed significantly, given the recurrent water shortage in the region. The considered irrigated areas were those of irrigated public perimeters, in the vicinity of the studied system. The irrigated areas are shown in Table 2.

b.2) Supply demand

The supply water demand was estimated based on the estimated population growth, with a project horizon for the year 2035 and per capita consumption.

For population growth, the demographic growth trends method was used. This method consists of dividing a larger area, where its estimative is already known, into smaller areas. The Brazilian Institute of Geography and Statistics (IBGE, 2016) made the population estimate of Brazil (bigger area) until the year 2050 using the method of demographic components. Their results served as data base to estimate the population of the cities of interest.

The criteria adopted by the Companhia de Água e Esgoto da Paraíba - CAGEPA (2011) were used to estimate per capita consumption, plus supply losses. It adopts that the losses of the supply system of Paraíba are of the order of 40%. The criteria adopted by CAGEPA for estimating per capita consumption vary according to population and are presented in Table 3.

Hydric demand scenario

The following scenarios have the function of quantifying the losses by evaporation, infiltration and reservoirs spilling processes of the exogenous flow of PISF that will occur along the Paraíba River. For this, seven scenarios of water demands were studied. The simulated municipalities in each scenario, with their respective pipeline system, are presented in Table 4.

O The summary of flows, demands and the water paths of pipeline systems for each simulated scenario are presented in Table 5. The pipeline traces of the simulated systems are shown in Figures 3 and 4.

a) Scenario 1

This scenario consists of the initial proposal of the Ministry of National Integration, without increasing the PISF flow and was based on the following specifications:

Table 2. Irrigated public perimeter demand.

Irrigated Perimeter	Area (ha)	Water Demand ($L.s^{-1}$)
Poções	356	160.20
Congo	156	70.20
Vereda Grande	289	130.05
Total	**801**	**360.45**

Table 3. The criteria adopted by CAGEPA (2011) for estimating per capita consumption.

# Number of inhabitants (P)	Consumption ($L.inh^{-1}.day^{-1}$) Per capita	Per capita +40% of losses
P ≤ 50.000	120	168
50.000>P≥150.000	150	210
P>150.000	200	280

> According to the PISF, all municipalities' water demands along the PISF axes must be met with local water resources or with transposed water. As a criterion, the PISF foresees that all sites located 10 km from the axes should have a guaranteed water supply to the population and urban economic activities. In addition to these cities, cities with more than 50,000 inhabitants located up to 50 km from the PISF axes should be treated equally (ANA, 2005, p. 20).

The municipalities that meet these specifications are presented in Table 4, with their respective water demands. The only municipality with more than 50 thousand inhabitants where its cityhall is located more than 10 km from the axis of the Paraíba River is Guarabira. Existing pipeline systems were also considered. Total system demand equals 2,539.27 l/s.

b) Scenario 2

It differs from Scenario 1 because of the increase in the exogenous flow from the São Francisco river. After meeting the demands, the rest of this PISF flow will serve as an ecological flow. From the Acauã reservoir onwards, these waters can still be used as reinforcement for the water supply of João Pessoa and for the integration channel.

In this scenario there is no construction of new channels and pipelines, reducing the amounts to be invested, since the PISF flow will be fully transported by the Paraíba River. However, the disadvantage will be in the high water losses in the system by evaporative and spillage processes, since the PISF waters will raise the water levels of the reservoirs, increasing the liquid surface, and there will still be losses in the transport due to the infiltration. Due to the water uncertainties, this scenario was simulated with a target volume in the reservoirs equal to its maximum.

The following scenarios were proposed by the AESA (2007), where a fraction of the PISF flow goes through pipeline systems and the rest will be transported by the Paraíba River. Two paths of pipeline systems were proposed, as shown in Figures 3 and 4. In both cases, the localities will benefit from new pipeline systems or by reinforcement of the existing ones. These scenarios comprise 108 municipalities totaling a demand of 3,649.55 l/s. The served municipalities with their respective water demands are presented in Table 4. In scenarios 2 to 7, the target volume of the reservoirs is 30% of their maximum volumes. This value was defined to minimize leakage losses, since the increase in PISF generates water safety, and it is no longer necessary to operate the reservoirs with the maximum possible volumes.

In Figures 3 and 4, Q1 is the PISF flow from the Poções dam, Q2 is the PISF flow from the Epitácio Pessoa reservoir (Boqueirão) and Qr is the PISF flow that will be transported through the Paraíba river bed from the Poções reservoir.

c) Scenario 3

This scenario considers a flow of 4,200 $L.s^{-1}$ of PISF, from the Poções reservoir, and the trajectory of the pipeline is shown in Figure 3. It foresees for the construction of a pipeline with a maximum capacity equal to Q1 = 2,000 $L.s^{-1}$ to meet the regions of Serra de Teixeira, Brejo, Curimataú, part of Cariri and Seridó and reinforcement to the Campina Grande supply system.

Table 4. Simulated cities on the scenarios.

<table>
<tr><th rowspan="2">Cities</th><th rowspan="2">Demand 2035 ($L.s^{-1}$)</th><th colspan="2">Pipeline system</th></tr>
<tr><th>Scenarios 1 and 2</th><th>Scenarios 3 to 7</th></tr>
<tr><td>Boqueirão</td><td>22.12</td><td rowspan="9">Cariri (Reforço ao manancial)</td><td rowspan="9">Cariri (Resource reinforcement)</td></tr>
<tr><td>Cabaceiras</td><td>6.24</td></tr>
<tr><td>Boa Vista</td><td>9.47</td></tr>
<tr><td>Soledade</td><td>24.85</td></tr>
<tr><td>Seridó</td><td>10.14</td></tr>
<tr><td>Olivedos</td><td>4.3</td></tr>
<tr><td>Juazeirinho</td><td>20.16</td></tr>
<tr><td>Cubatí</td><td>8.4</td></tr>
<tr><td>Pedra Lavrada</td><td>6.39</td></tr>
<tr><td>Campina Grande</td><td>1352.04</td><td rowspan="6">Boqueirão (Reforço ao manancial)</td><td rowspan="4">Campina Grande (Resource reinforcement)</td></tr>
<tr><td>Queimadas</td><td>50.54</td></tr>
<tr><td>Caturité</td><td>2.44</td></tr>
<tr><td>Barra de Santana</td><td>1.66</td></tr>
<tr><td>Riacho do Santo Antônio</td><td>3.01</td><td rowspan="2">Boqueirão (New system)</td></tr>
<tr><td>Barra de São Miguel</td><td>5.35</td></tr>
<tr><td>Pocinhos</td><td>22.02</td><td>Mamanguape (New system)</td></tr>
<tr><td>Alcantil</td><td>4.27</td><td>NS</td><td>Boqueirão (New system)</td></tr>
<tr><td>Congo</td><td>5.9</td><td rowspan="3">LR</td><td rowspan="11">Congo (Resource reinforcement)</td></tr>
<tr><td>Coxixola</td><td>2.25</td></tr>
<tr><td>Monteiro</td><td>48.3</td></tr>
<tr><td>Gurjão</td><td>4.72</td><td rowspan="8">NS</td></tr>
<tr><td>Livramento</td><td>6.84</td></tr>
<tr><td>Parari</td><td>1.13</td></tr>
<tr><td>Santo André</td><td>1.46</td></tr>
<tr><td>São João do Cariri</td><td>4.25</td></tr>
<tr><td>São José dos Cordeiros</td><td>2.98</td></tr>
<tr><td>Serra Branca</td><td>17.57</td></tr>
<tr><td>Sumé</td><td>32.57</td></tr>
<tr><td>Natuba</td><td>5.95</td><td rowspan="3">LR</td><td rowspan="3">Natuba (Resource reinforcement)</td></tr>
<tr><td>Santa Cecília</td><td>3.24</td></tr>
<tr><td>Umbuzeiro</td><td>7.24</td></tr>
<tr><td>Fagundes</td><td>10.4</td><td>NS</td><td rowspan="2">Acauã Norte (New system)</td></tr>
<tr><td>Itatuba</td><td>12.9</td><td>LR</td></tr>
<tr><td>Ingá</td><td>26.1</td><td rowspan="3">NS</td><td rowspan="4">Acauã Norte (Resource reinforcement)</td></tr>
<tr><td>Juarez Távora</td><td>14.36</td></tr>
<tr><td>Riachão do Bacamarte</td><td>6.43</td></tr>
<tr><td>Mogeiro</td><td>10.28</td><td>LR</td></tr>
<tr><td>Aroeiras</td><td>16.42</td><td rowspan="2">NS</td><td rowspan="2">Acauã - Oeste (Resource reinforcement)</td></tr>
<tr><td>Gado Bravo</td><td>1.48</td></tr>
</table>

Legend: LR= supply from Paraiba river bed; NS = not reached by this simulation scenario.

Table 4. Continuação...

Cities	Demand 2035 ($L.s^{-1}$)	Pipeline system	
		Scenarios 1 and 2	Scenarios 3 to 7
Itabaiana	38.86	LR	Acauã - Leste (New system)
Juripiranga	22.86		
Salgado de São Félix	11.88		
Pilar	20.47		
São Miguel de Taipu	7.38		
Bayeux	278.38	LR	Rio Paraíba (Paraíba's bedriver water sypply)
Cruz do Espírito Santo	18.13		
Santa Rita	315.33		
Caldas Brandão	6.62	NS	São Salvador (Via Integration channel)
Gurinhém	11.12		
Mari	34.18		
Mulungu	8.78		
Sapé	70.82		
Sobrado	1.96	LR	
Araçagi	12.37	NS	Araçagi – Oeste (Via Integration channel)
Cuitegi	11.04		
Pilõezinhos	5.04		
Guarabira	139.45	LR	
Itapororoca	26.84	NS	Araçagi – Leste (Via Integration channel)
Mamanguape	75.59		
Rio Tinto	29.22		
Camalaú	6.3	LR	NS
Caraúbas	3.92		
São Domingos do Cariri	2.44		
Riachão do Poço	3.02		
São José dos Ramos	5.82		
Arara	21.24	NS	Arara (Resource reinforcement)
Casserengue	6.98		
Belém	31.67	NS	Belém (Resource reinforcement)
Caiçara	9.88		
Logradouro	4.81		
Araruna	28	NS	Canafistula II (Resource reinforcement)
Bananeiras	16.54		
Cacimba de Dentro	17.88		
Campo de Santana	8.42		
Damião	8.02		
Dona Inês	10.68		
Riachão	6.07		
Solânea	38.16		
Cuité	27.26	NS	Cuité (Resource reinforcement)
Nova Floresta	22.6		
Alagoa Grande	32.75	NS	Mamanguape (New system)
Alagoa Nova	20.79		
Algodão de Jandaíra	2.76		
Areia	28.04		
Areial	9.22		
Esperança	50.36		
Lagoa Seca	20.8		
Matinhas	1.38		
Montadas	8.31		
Puxinanã	9.76		
Remígio	34.05		
São Sebastião de Lagoa de Roça	11.17		
Serraria	6.46		

Legend: LR= supply from Paraiba river bed; NS = not reached by this simulation scenario.

Table 4. Continuação...

Cities	Demand 2035 ($L.s^{-1}$)	Pipeline system	
		Scenarios 1 and 2	Scenarios 3 to 7
Duas Estradas	5.5	NS	Pirpirutuba (Resource reinforcement)
Lagoa de Dentro	8.25		
Pirpirituba	15.3		
Serra da Raiz	3.89		
Serraria	6.46		
Borborema	8.25		
Sertãozinho	9.73		
Cacimbas	3.23	NS	Serra de Teixeira (Resource reinforcement)
Desterro	9.81		
Imaculada	9.7		
Mãe d'Água	4.68		
Maturéia	10.58		
Taperoá	24.04		
Teixeira	27.27		
Barra de Santa Rosa	13.75	NS	Seridó (New system)
Sossego	4.08		
Baraúna	9.34		
Nova Palmeira	9.34		
Frei Martinho	3.32		
Picuí	26.52		

Legend: LR= supply from Paraiba river bed; NS = not reached by this simulation scenario.

Table 5. Flow rate and alternative to water transport.

Scenario	Flow ($L.s^{-1}$)				Demand ($L.s^{-1}$)	Water transport
	PISF	Qr	Q1	Q2		
1	-	-	-	-	2,540	River
2	4,200	4,200	-	-	2,540	River
3	4,200	2,200	2,000	-	3,650	Alternative 1
4	4,200	2,150	250	1,800	3,650	Alternative 2
5	4,200	3,080	1,120	-	3,650	Alternative 1
6	4,200	2,950	250	1,000	3,650	Alternative 2
7	10,000	2,000	8,000	-	3,650	Alternative 1

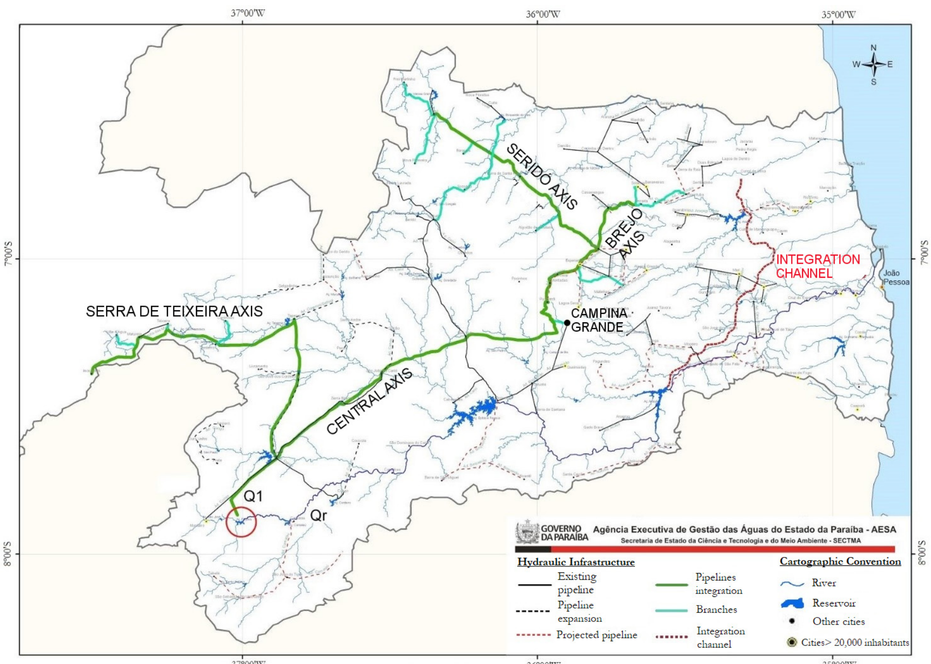

Figure 3. Alternative 1 for the paths of the water pipeline systems, AESA (2007).

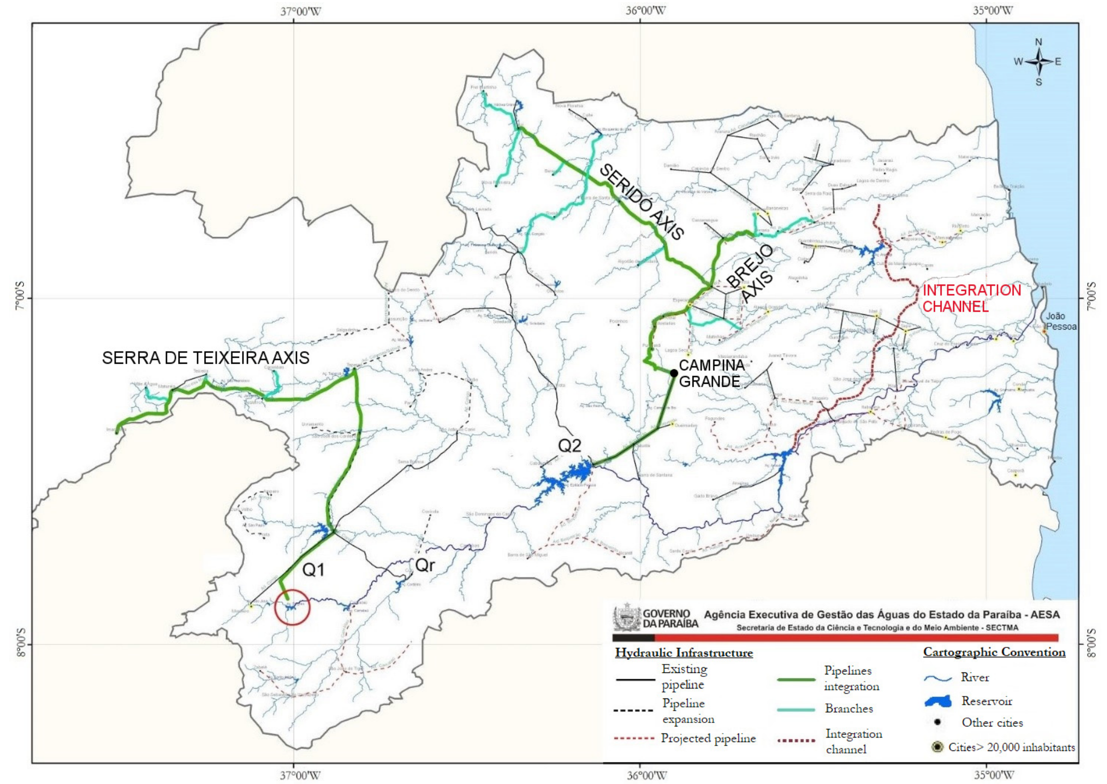

Figure 4. Alternative 2 for the paths of the water pipeline systems, AESA (2007).

The remains follows along the bed of the Paraíba river with a flow of Qr = 2,200 $L.s^{-1}$.

d) Scenario 4

This scenario considers a flow of 4,200 $L.s^{-1}$ of the PISF and the pipelines will follow the lines of Figure 4, where the central axis set out in Scenario 3 is withdrawn and it is maintained the pipeline to the Serra de Teixeira, with a maximum flow equal to Q1 = 250 $L.s^{-1}$. The rest would be released on the Paraíba River. From the Epitácio Pessoa Dam, a reinforcement flow to the pipeline system of Campina Grande would come out. This pipeline would still supply the regions of Brejo, Curimataú and Seridó, with a maximum expected flow for Q2=1,800 $L.s^{-1}$.

e) Scenario 5

The PISF flow for this scenario will be 4,200 $L.s^{-1}$ and the lines of the pipeline system is the same as the one shown in Figure 3. This alternative differentiates from Scenario 3 by eliminating the reinforcement flow to Campina Grande from the PISF central axis and placing it from the Epitacio Pessoa dam. In this scenario, a maximum flow of Q1 = 1,120 $L.s^{-1}$ was transported by pipeline from the Poções reservoir and the remainder of the flow would be transported through the river bed, ie, Qr=3,080 $L.s^{-1}$.

f) Scenario 6

This scenario considers a flow of 4,200 $L.s^{-1}$ of the PISF and the route of the pipeline system is shown in Figure 4, where Q1 = 250 $L.s^{-1}$ to meet the required flow to the Serra de Teixeira Axis. The water supply of the Brejo, Curimataú and Seridó regions would be done by means of a pipeline system from the Epitácio Pessoa dam with a maximum capacity equal to Q2 = 1,000 $L.s^{-1}$, but without the inclusion of the Campina Grande reinforcement.

g) Scenario 7

This scenario considers a PISF flow of 10,000 $L.s^{-1}$. From the Poções reservoir, the trajectory of the pipeline system is the same as shown in Figure 3. It foresees for the construction of a pipeline system with a maximum capacity of Q1 = 2,000 $L.s^{-1}$, to meet water demand of the regions of Serra de Teixeira, Brejo, Curimataú, part of Cariri and Seridó and reinforce the flow to the Campina Grande system. The remainder would follow along the bed of the Paraíba river, with Qr = 8,000 $L.s^{-1}$. It has the purpose of evaluating the maximum flow rate in Acauã with 100% guarantee to meet the Integration Channel.

System performance indicators

Water resources projects use a large amount of data, which makes the direct comparison between different management proposals a very difficult task. To make a comparison it is necessary to create evaluation parameters that retain only essential data, which are called of performance indicators.

a) Reliability

Reliability (Conf) is the probability that all demands are met without failure, that is, it is the percentage of time that all the water demands were met.

$$\text{Conf} = \text{prob}\{V_t \in S\} = \frac{N_S}{N} \tag{1}$$

Where:

Ns: is the number of successes in the simulated period of time *N*.

b) Resilience or elasticity

Resilience (res) is used to evaluate the average of how quickly the system returns from a failure *(F)* state to a satisfactory *(S)* demand-service state. The resilience of the reservoir is the probability of a satisfactory state occurring in period t + 1 (V_{t+1}) given an unsatisfactory value in period t.

$$res = Prob\{V_{t+1} \in S / Vt \in F\} \quad (2)$$

Where:
res: is the number of times the reservoir exits a fault/total number of faults.

In some cases a system that has many failures is preferable, since it recovers quickly, than one that has few failures and that recovers slowly.

c) Vulnerability

Vulnerability (vul) indicates how severe the magnitude of the system failure is, if it has occurred. It can be defined as the average of the percentage of water deficits of all values of the set F. Mathematically we have:

$$vul = \frac{1}{nf}\sum_{t}\left|\frac{V_t - Vd_t}{Vd_t}\right| \quad (3)$$

Where:
nf: is the number of failure events, V_t is the supplied water at time t and Vd_t is the demand required at time *t*.

d) Sustainability

Loucks (1997) apud Vieira (2007), proposed a general sustainability index (Sust) defined by:

$$Sust = Conf * res * (1\text{-}vul) \quad (4)$$

e) Efficiency indexes associated to the reservoirs

In this work, the efficiency indexes associated to the reservoirs are used to compare scenarios of water demand with and without PISF under different forms of water transportation. Through them, it is aimed to determine which scenarios have obtained the lowest losses in the system, be they by spilling, by evaporation or in transit through infiltration, and also to evaluate the water yields of each scenario.

The following are some efficiency indicators associated with reservoir operation. These indicators are based on its water balance equation.

η_{Vr} - relation between the volumetric variability of the reservoir and the total annual affluent volume. This index indicates the interannual variability of the reservoir volume.

$$\eta_{Vr} = \frac{Vr_{final} - Vr_{inicial}}{\sum Qat + \sum Pt} \quad (5)$$

Where:
$Vr_{inicial}$ e Vr_{final}: are the initial and final volumes of the reservoirs respectively. Qat and Pt are respectively the monthly affluent and precipitated volumes in the watershed.

Negative values indicate reservoir depletion (e.g.: years of drought) and positive ones indicates water accumulation/gain in the reservoir.

η_E - relation between the evaporated volume (Et) (reservoir surface) and the total annual inflow:

$$\eta_E = \frac{\sum Et}{\sum Qat + \sum Pt} \quad (6)$$

Where:
Et: reservoir monthly evaporation.

This index has as characteristics:

✓ Establish water storage efficiency;
✓ It may indicate that the reservoir has low depth and large area of the liquid mirror;
✓ Can be used to establish how fast the water has to be used to reduce evaporative losses;

η_P – Is the relationship between direct precipitation over the reservoir hydraulic basin (reservoir liquid surface) and the total annual affluent volume. This index indicates the percentage of direct precipitation on the hydraulic basin of the reservoir:

$$\eta_P = \frac{\sum Pt}{\sum Qat + \sum Pt} \quad (7)$$

Where:
Pt: reservoir direct precipitation
✓ This index may indicate that the reservoir has low depth and large area of the liquid mirror;
✓ High rates indicate that the contribution basin is small.

η_V - Relation between the spillage volume (QVt) and the total annual affluent volume:

$$\eta_V = \frac{\sum QVt}{\sum Qat + \sum Pt} \quad (8)$$

Where:
QVt: last reservoir spillage

This index has as characteristics:

✓ Establish the water storage efficiency (losses) or relative reservoir capacity;
✓ Indicates how much the reservoir wastes away the water inflow by spillage;

η_u - Relation between the used water volume (*Qut*) (dischargers, water intakes) and the water inflow (water yields):

$$\eta_u = \frac{\sum Qut}{\sum Qat + \sum Pt} \quad (9)$$

Where:
Qut: reservoirs water volume withdraw (to supply urban demand, animal watering and irrigation)

This index has as characteristics:

✓ Establishs the water amount used regarding to the affluent volume;
✓ High rates indicate that there are few losses;

Based on the equation of the water balance, the volumetric variation in the reservoir *(ΔVr)* is described as the difference between the sums of the incoming *(ΣQentrada)* and exiting *(ΣQsaida)* flows from the reservoir:

$$\Delta Vr = Vr_{final} - Vr_{inicial} = \sum Q_{entrada} - \sum Q_{saída}$$

$$Vr_{final} - Vr_{inicial} + \sum Q_{saída} = \sum Q_{entrada} \quad (10)$$

Knowing that:

$\sum Q_{entrada} = \sum Qat + \sum Pt$, and also

$$\sum Q_{saida} = \sum Et + \sum QVt + \sum Qut$$

Equation 10 may be written as:

$$Vr_{final} - Vr_{inicial} + \sum Et + \sum QVt + \sum Qut = \sum Qat + \sum Pt \quad (11)$$

Dividing Equation 11 by the mathematic expresion $\sum Q_{entrada} = \sum Qat + \sum Pt$, yields:

$$\frac{Vr_{final} - Vr_{inicial} + \sum Et + \sum QVt + \sum Qut}{\sum Qat + \sum Pt} = \frac{\sum Qat + \sum Pt}{\sum Qat + \sum Pt} \quad (12)$$

Based on Equations 5, 6, 8 e 9. The Equation 12 may be rewritten this way:

$$\eta_{Vr} + \eta_E + \eta_V + \eta_u = 100\% \quad (13)$$

Considering that Equation 13 is based on the water balance, then it can be expanded to an integrated system of reservoirs or even to the river basin as a whole, by inserting a term (ηpt) that relates the losses in transit through infiltration that occur in the river bed and the total annual tributary flow.

$$\eta_{pt} = \frac{\sum Q_{pt}}{\sum Qa_t + \sum P_t} \quad (14)$$

Where:
Qpt: is the volume of water lost in transit in the river bed by infiltration. Thus, Equation 13 can be rewritten as:

$$\eta_{Vr} + \eta_E + \eta_V + \eta_u + \eta_{pt} = 100\% \quad (15)$$

Other indicators associated with the reservoirs were used by Vieira (1996). However, these indexes were adapted for surface water analysis. In this case, the indicators associated to the reservoirs *potentiality* is obtained by the sum of the inflows plus the direct precipitation and the reservoirs *Availability* equals the sum of inflows plus direct precipitation minus losses; The water demands are consumptive uses (water intakes for human supply and irrigation). Within this context the following indexes are defined:

Potential Activation Index (IAP) is defined as the ratio between availability and potentiality:

$$IAP = \frac{Availability}{Potenciality} = 1 - losses = 1 - \eta_E - \eta_V - \eta_{pt} = \eta_{Vr} + \eta_u \quad (16)$$

Availability Utilization Index (IUD) is the ratio of demand to availability:

$$IUD = \frac{Water \quad Demand}{availability} = \frac{\eta_u}{\eta_{Vr} + \eta_u} \quad (17)$$

Potential Utilization Index (IUP) is the ratio of demand to potentiality.

$$IUP = \frac{Water \quad Demand}{Potentiality} = \eta_u \quad (18)$$

Such indexes can also be applied to the integrated reservoir system, where all inflows entering the system plus direct precipitation over the reservoirs form the *potentiality*. *Availability* is the potentiality minus the losses in transit, evaporations in the reservoirs and spillage volumes in the river bed downstream of the system. The demands are all consumptive uses (human supply and irrigation).

As each scenario met different demands, given the layout of the pipeline systems, information was also included about the increase in demand in relation to Scenario 1 (without the transposition), called *%Dem*.

RESULTS AND DISCUSSION

Water losses calculations

The total losses in the system are the losses resulting from the processes of evaporation, spillage and losses in transit along the river by infiltration. As the river dynamics in the Paraíba river basin is the same in all scenarios, then the calculation of the total water losses of the PISF flow in the system is done according to Equation 19:

$$Losses(Ci) = \frac{\sum Losses(C1) - \sum Losses(Ci)}{Q_{PISF}} x100\% \quad (19)$$

Where:
Losses (Ci): Total water losses on Scenario i, with *i= 2,..., 7*;
Losses (C1): Total water losses on Scenario 1, (scenario which there was no transposition);
QPISF: Exogenous flow of PISF.

All losses were transformed into average flow in $L.s^{-1}$, and their results for each scenario are presented in Table 6, as well as, the regularized flows from Acauã.

In this research priorities were adopted to meet the demands and the target volumes of the reservoirs. In the used model the lowest value priority indicates the water use that would be first served. The priorities for each simulated water use are given in Table 7.

The priorities are to meet urban water supply first, following the regularized flow in the Paraíba river bed downstream of the Acauã reservoir and, finally, the target volumes of the reservoirs. All scenarios foresee for the supply of cities with the direct water catchment of the Paraíba river. In Scenario 2 all water would be transported via the river bed, thus, the upstream water demands of the cities would have higher priority than the downstream ones. The choice of this sequence of priorities is due to the policy of privileging the service from upstream to downstream.

Table 6. PISF flow rate, demanded and system water losses.

Scenarios	PISF Flow rate (L.s^{-1})	Demand (L.s^{-1})		Flow rate (L.s^{-1})		PISF Water losses			
		Supply	Irrigation	Lost from PISF	Regularized	Evaporation (%)	In transit (%)	Leakage (%)	Total (%)
Scenario 1	-	2,540	360	-	-	-	-	-	-
Scenario 2	4,200	2,540	360	2,540	1,630	6.87	16.93	36.56	60.36
Scenario 3	4,200	3,650	360	1,910	1,110	5.50	9.86	30.05	45.41
Scenario 4	4,200	3,650	360	2,240	790	5.84	13.31	34.08	53.23
Scenario 5	4,200	3,650	360	2,030	980	5.65	11.14	31.60	48.39
Scenario 6	4,200	3,650	360	2,240	790	5.85	13.31	34.08	53.24
Scenario 7	10,000	3,650	360	4,850	4,040	3.42	26.06	18.97	48.46

Table 7. Priorities of demand meeting and goal volumes on reservoirs.

Demand	Scenarios						
	1	2	3	4	5	6	7
Poções	1	1	-	-	-	-	-
Camalaú	2	2	1 to 4[a]	1 and 2[a]	1 to 4[a]	1 and 2[a]	1 to 4[a]
Boqueirão	3[b] and 4	3[b] and 4	5[b] and 6[a]	3 to 5	5	3 to 5	5[b] and 6[a]
Acauã	5[b] and 6	5[b] and 6	7 to 8	6 to 8	6 to 8	6 to 8	7 to 8
Regularized flow downstream Acauã	7	7	9	9	9	9	9
Leakage on Acauã	99	99	99	99	99	99	99
Irrigation Poções	9	9	10	10	10	10	10
Irrigation Cordeiro	10	10	11	11	11	11	11
Irrigation Vereda Grande	11	11	12	12	12	12	12
Reservoirs	**Priority of goal volume of the reservoirs**						
Poções	20	20	20	20	20	20	20
Camalaú	30	30	30	30	30	30	30
Boqueirão	40	40	40	40	40	40	40
Acauã	50	50	50	50	50	50	50

[a]Pipeline system yet to be installed, the number goes from downstream to upstream; [b]Existing pipeline systems.

System performance indicators calculation

In Scenarios 2 to 7, due to the increase in the PISF, there were no failures to meet the demands and, therefore, their performance indicators were the best possible, ie reliability, resilience and sustainability were equal to 100%, since the vulnerability was equal to 0%.

Scenario 1 was simulated without transposition and there were failures in the supply and irrigation demands for the Poções and Camalaú reservoirs. Its performance indicators are presented in Table 8.

Analyzing the results of Scenario 1, the Poções and Camalaú reservoirs collapsed for a consecutive period of 21 and 20 months, respectively, reflecting the low resilience index, high vulnerability index and low sustainability in meeting the demands.

The efficiency indexes for the integrated reservoir system are presented in Table 9. The series of data that generated the indicators and indices are found in Farias (2009).

Based on Table 9, it was verified that Scenario 1 presented the highest loss indexes η_V and η_E, associated to spillage and evaporative losses, respectively. This fact occurs because the simulation was performed without transposition, and it was established that the target volume is equal to the maximum volume, which increases the reservoir liquid surface and, consequently, increases the evaporative losses and by spillage. Scenario 7 presented the highest ηu index, since it receives a flow of 10,000 L.s^{-1} from the PISF, generating an increase in the water supply. In the other scenarios with transposition this index did not change significantly, being the second largest value with Scenario 3, because it was simulated with the highest flow rate from the Poções reservoir, which reduces the losses in transit, increasing the availability.

Scenarios 4 and 6 obtained very close indexes, with no significant water performances differences, with regard to the volume of water added from the Boqueirão reservoir. They differ only in the way in which the water will be transported, since Scenario 4 foresees the water reinforcement to the supply of Campina Grande through the route that goes to the Brejo. In Scenario 6, water reinforcement will be done by another independent pipeline system.

Among the scenarios with transposition, Scenario 3 was the one that obtained the lowest index ηpt of water losses in transit in relation to the inflows. Scenario 7 presented the highest value, since it was transported in it a larger flow through the bed of the Paraíba river. For the other scenarios with transposition there were no significant variations, since the greatest losses in traffic occur downstream of the Boqueirão dam.

Table 8. Performance indicators for Scenario 1.

Water Demands	Reliability (%)	Resilience (%)	Vulnerability (%)	Sustainability (%)
Poções	91.24	14.52	87.42	1.67
Camalaú	93.64	15.56	85.56	2.10
Boqueirão	100	100	0.	100.00
Acauã	100	100	0	100.00
Irrigation Poções	89.97	12.68	93.75	0.71
Irrigation cordeiro	92.66	15.38	98.08	0.27
Irrigation vereda grande	100	100	0	100

Table 9. Efficency indexes associated to the reservoir system.

Indexes	Scenario 1* (%)	Scenario 2 (%)	Scenario 3 (%)	Scenario 4 (%)	Scenario 5 (%)	Scenario 6 (%)	Scenario 7 (%)
η_{Vr}	-0.62	-0.30	-0.31	-0.34	-0.32	-0.34	0.42
η_{E}	33.42	30.98	30.92	30.72	30.86	30.73	23.82
η_{V}	30.29	21.80	21.94	22.20	22.03	22.20	14.40
η_{u}	18.30	22.48	25.30	23.77	24.69	23.77	30.61
η_{pt}	18.60	25.05	22.17	23.65	22.74	23.64	31.59
IAP	19.92	23.97	26.78	25.23	26.17	25.23	31.61
IUD	91.87	93.76	94.46	94.19	94.35	94.19	96.68
IUP	18.30	22.48	25.30	23.77	24.69	23.77	30.61
%Dem	0	0	38.29	38.29	38.29	38.29	38.29

*Scenario without the transposition.

CONCLUSION

Analyzing the obtained results, it was verified that the initial proposal of the Ministry of National Integration (Scenario 2) is subject to high transportation losses caused by infiltration and evaporation along the river and, in addition, losses occur in the reservoirs by evaporation and spillage. In this scenario, in addition to the water losses being greater in relation to the others, there is a reduction in the coverage area of the project, since it does not foresee for the construction of new pipelines or channels systems and only the existing pipelines systems would receive the water reinforcement of the transposition. Without these works to bring the waters of the PISF to the interior of the state, there is no increase in water supply for this region, which will continue to depend on climatic phenomena and being vulnerable to water scarcity.

Scenario 3 was the one that presented the lowest water loss, because it shows higher flow in relation to the other scenarios taken from Poções. Scenario 5 also presented good water performance, however, for the construction of new water pipeline system, more detailed studies should be made regarding to the path and their capacities, since these works involve high implantation and operation costs throughout its useful life. By this factor the construction of pipelines with the characteristics of scenarios 4 and 6 may be one of the most feasible economically.

Scenario 7 was simulated to determine which flow would be regularized from the Acauã reservoir when the system receives the maximum flow predicted in the PISF for the East Axis in Paraíba, which is 10,000 $L.s^{-1}$ continuously. However, the PISF predicts that the system will only receive this flow in rainy periods in the São Francisco River Basin, and not in any simulated period. Among the scenarios that received 4,200 $L.s^{-1}$ of the transposition, Scenario 1 is the one with the highest losses, since it has a demand of 30.41% lower in relation to the other scenarios with transposition. This increases the water availability and, consequently, the regularized flow, however the number of cities and the population served are smaller.

Taking into account water losses, indexes and performance indicators, the construction of new pipeline systems is indispensable for the successful transposition of the São Francisco River. These works, in addition to significantly reducing the water losses of the PISF flow along the Paraíba River, also increase the scope of action of the project, since there is an increase, both, in the population and in the served water demands, providing support, with the guarantee of water, to the region's economic and social development.

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Authors contributions

Emmanuel Eduardo Vitorino de Farias: Work conception, Data analysis and processing, discussion of the results and writing of the article.

Wilson Fadlo Curi: Study orientation, Text revision elaboration of the Abstract and analysis of the results.

Laudizio da Silva Diniz: Definition of simulated scenarios and methodology, Text revision.