Supplementary Document

A Water Allocation Model for Multiple Uses Based on a Proposed Hydro-economic Method

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1. São Francisco Water Transboundary Characterization

The project to transfer a portion of the water from the São Francisco River to the northernnortheastern region dates to Brazil's imperial period in the 1818s [43] a path to mitigate droughts in the northern northeast. Initially, the project was designed to bring water from the Cabrobó region in Pernambuco to the Jaguaribe River in Ceará [43]. Since the imperial period, the transposition project has been revised and expanded, and its license to install the works was obtained in 2007.

The current transposition is called the São Francisco Integration Project (PISF), however is used the Sao Francisco Transboundary System (SFTS) in the manuscript the system composes of the PISF and the Sao Francisco River infrastructure. The SFTS associated branches and interconnections to promote water security for approximately 12 million people. The PISF covers 390 municipalities in the states of Pernambuco, Ceará, Paraíba and Rio Grande do Norte. This region suffers from long recurring droughts [43]. The two structuring lines have a total length of approximately 477 km, with another 345 km of branches and interconnections. Altogether on its completion the PISF has 27 reservoirs, 9 pumping stations, 13 aqueducts, 9 x 230 kW substations, 270 km of high voltage line and 4 tunnels. The branches and interconnections are crucial for the permeation of the transposed waterto the destination locations, mostly decentralized in relation to the structuring lines. The total cost of the construction is estimated at R$ 12 billion, approximately US $ 2.26 billion (US $ 1.00 = R$ 5.30). Figure 5 of manuscript illustrates the location and implementation planned for PISF in the SFTS take into consideration for the model application. The model application was based on [41,42,43].

The priority use of the PISF waters is for human and animal water supply. Uponcompletion of the works, it is expected that approximately 12 million people will benefitfrom the PISF waters, and currently 77 municipalities are expected to receive waters, totaling 1.5 million inhabitants. Of these municipalities, 13 are located in Pernambuco, 18in Ceará, 27 in Paraíba and 19 in Rio Grande do Norte.

The water withdrawal allowed by water national agency (ANA) through Resolution 411/2005 is a constant flow in both lines of 26.4 m^3/s. The main function of this constant flow is to serve human consumption and animal watering. If Sobradinho reservoir level is between 94% of the useful volume and the waiting volume for flood control, it is allowed to pump an average daily flow of 114.30 m^3/s and an instantaneous flow of up to 127 m^3/s.

North Line

The northern line is divided into two sections (I and II). Its water intake is in theSão Francisco River near Assunção Island, in the municipality of Cabrobó, PE. The water pumped to the Engenheiro Ávidos Reservoir in Cajazeiras, PB. The northern line serves through municipalities of Ceará and has a total length of 260 km.

Section I of the northern axis runs from the water intake to the Engenheiro Hilton Timóteoreservoir, also known as the Jati Reservoir. This stretch has the capacity to convey flows of up to 99 m^3/s and has 3 pumping stations to overcome 169 meters of topographical difference. This stretch is approximately 114 km long in channels, 5 aqueducts totaling 675 m, 1 tunnel approximately 500 meters long, and 6 reservoirs.

Section II of the northern axis starts at the Jati reservoir up to the reservoir of EngenheiroÁvidos, PB. The beginning of this stretch has the capacity to conduct flows of up to 99 m^3/s, increasing to 53.8 m^3/s in the outflow channel in the Engenheiro Ávidos reservoir. This stretch is approximately 40 km long in channels, 3 aqueducts totaling 510 m, 2 tunnels totaling 19 km and 9 reservoirs.

Supplementary Table 1. Summary of North line characteristic

Structure	Quantity	Total
Channels	33	158.47 km
Aqueduct	8	1.36 km
Reservoir	16	675.55 hm^3
Pumping stations	3	213.6 MW (capacity)

Eastern Line

The eastern line has its intake located in the Itaparica (Luiz Gonzaga) reservoir on the São Francisco River.The waters are pumped to the Poções Dam in Paraíba. The eastern line passes through Pernambuco and Paraíba municipalities and has a total length of 217 km.

The eastern line has a topographic difference of 332 m and its flow conduction capacity is up to 28 m^3/s, reaching the end with a capacity of 8 m^3/s. Overall, the eastern line has 176.2 km of canals, 5 aqueducts, 1 tunnel, 1 adductor 6 pumping stations and 14 reservoirs.

Supplementary Table 2. East line characteristic summary

Structure	Quantity	Total
Channels	24	176.20 km
Aqueduct	5	7.59 km
Reservoir	14	37.94 hm^3
Pumping stations	6	92.54 MW (capacity)

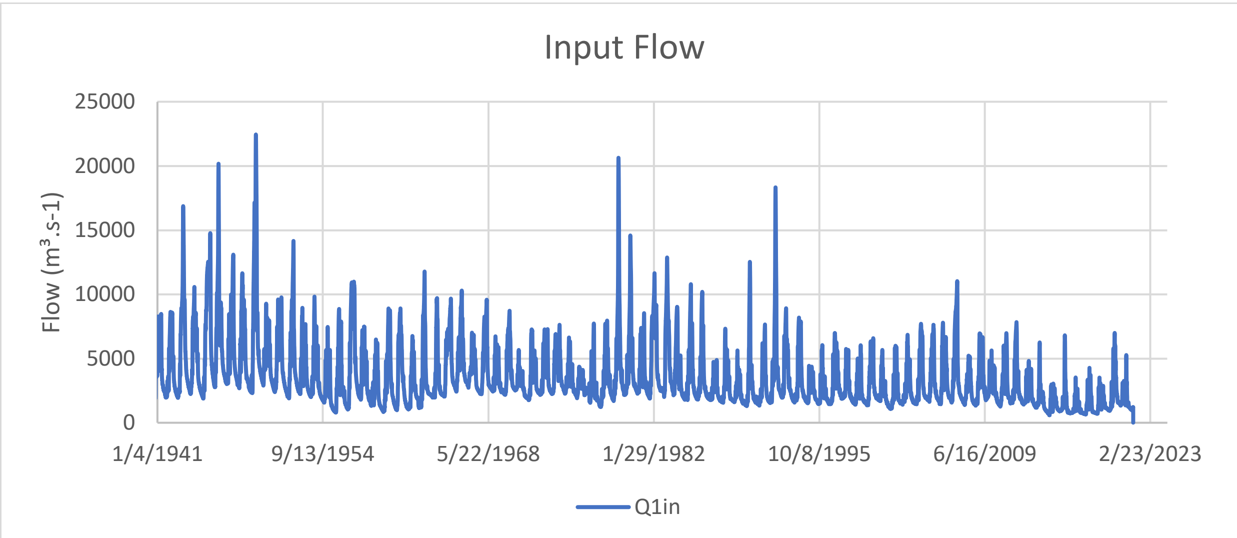
A total of 713.49 hm^3 of water will be stored in reservoirs and a length of at least 343.62 km of canals and aqueducts. The accumulated topographical difference in both lines is 501 m. The installed capacity to serve the constant flow in both axes sums 38.75 m^3/s, where 24.75 m^3/s is in the north line and 14 m^3/s is in the east axis. The total capacity foreseen in the project to meet water demands has an instantaneous maximum flow of 127 m^3/s, where 99 m^3/s is foreseen for the northern axis and 28 m^3/s on the eastern axis [41].

2. Discharge-in for Model Application

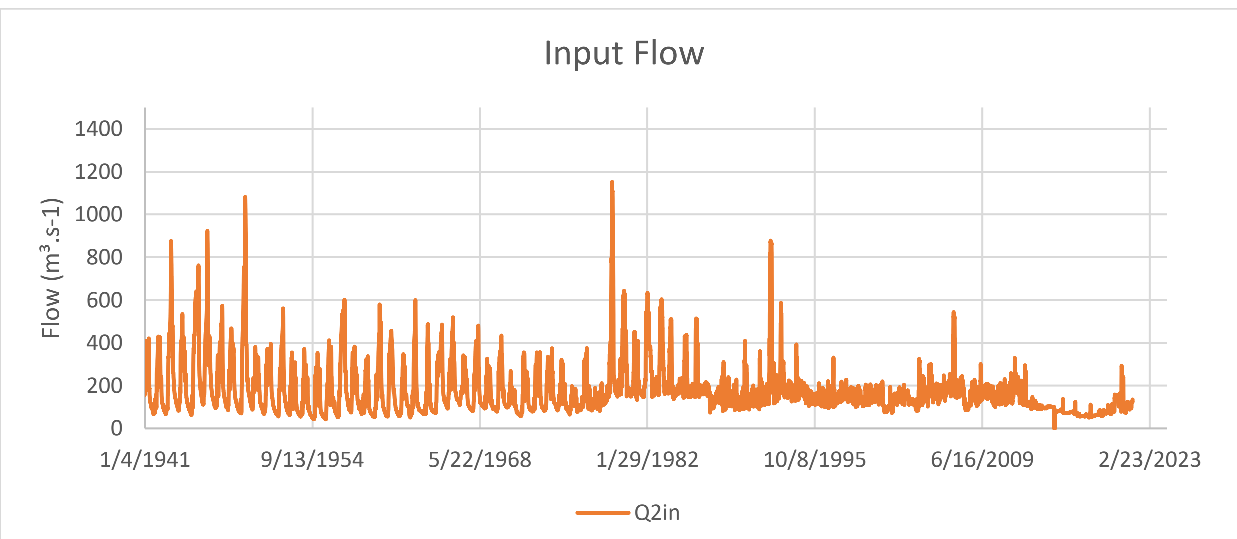
The natural flow was based on a hydrometric gauge station provided by the water national agency (ANA[1]). Due to the basin size and the period of registered flow, was possible to cover the time frame between 1941 and 2021. The data of hydrometric gauge station is available at ANA (water national agency). The time-series of flow was reconstructed to capture the natural flow, without the water abstraction, reservoirs, and Dams. The Supplementary Figure 1 to 5 presents the daily flow was considered in the model

[1] Hydrometric gauge station code: 46902000, 46360000, 45298000, 48020000, 48590000, 49042580, 48860000, 49160000, 49370000, and 48290000. The data source is available at https://www.snirh.gov.br/hidroweb/apresentacao.

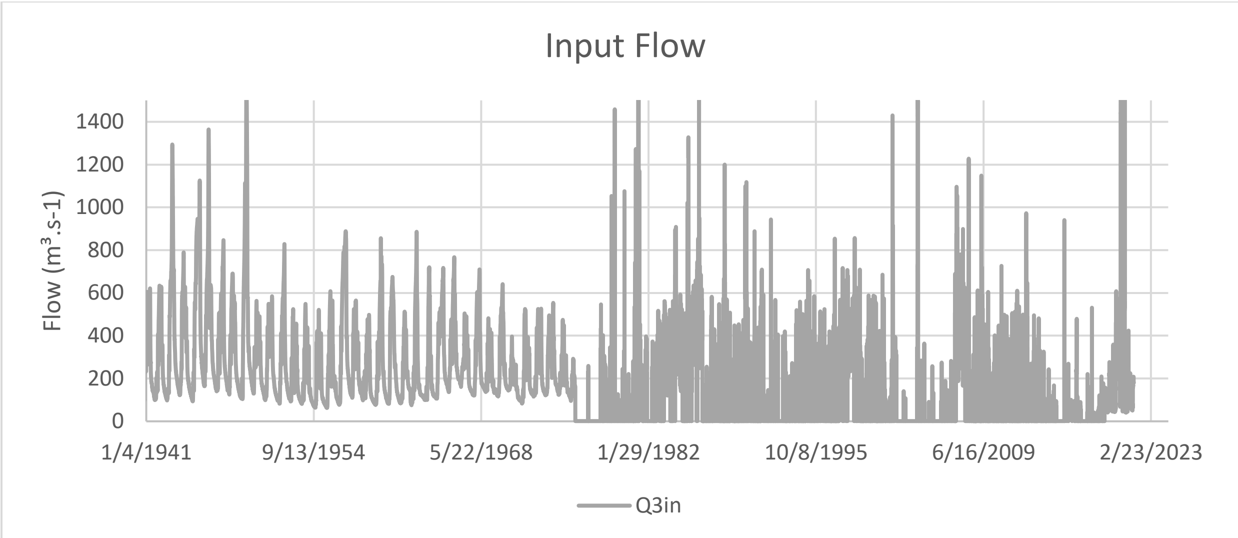
application. Is important to mention the flow input was converted to volume per day for the model application. Q1in is the flow input upstream of Sobradinho Reservoir, and the Q2in, Q3in, Q4in and Q5in are the incremental flow input for the downstream Dams. All dataset input for model applications is fully open and available at https://github.com/wdvichete84/sustainable_waterAllocation_model.git. Also, a repository with the same data was published by [44].



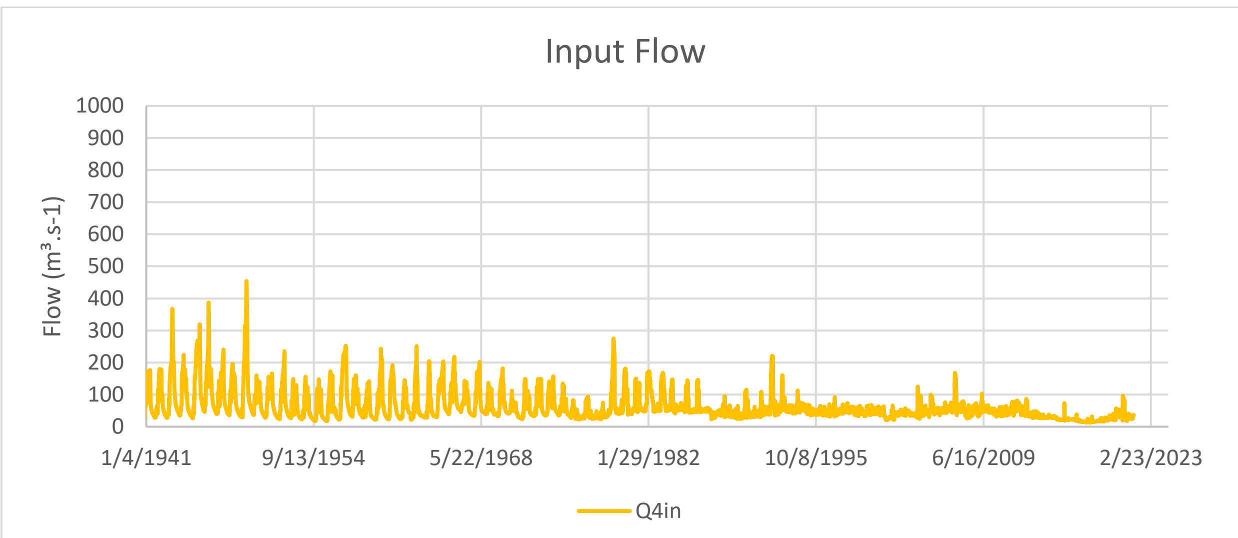
Supplementary Figure 1. Daily flow input for model application upstream of Sobradinho Hydropower.



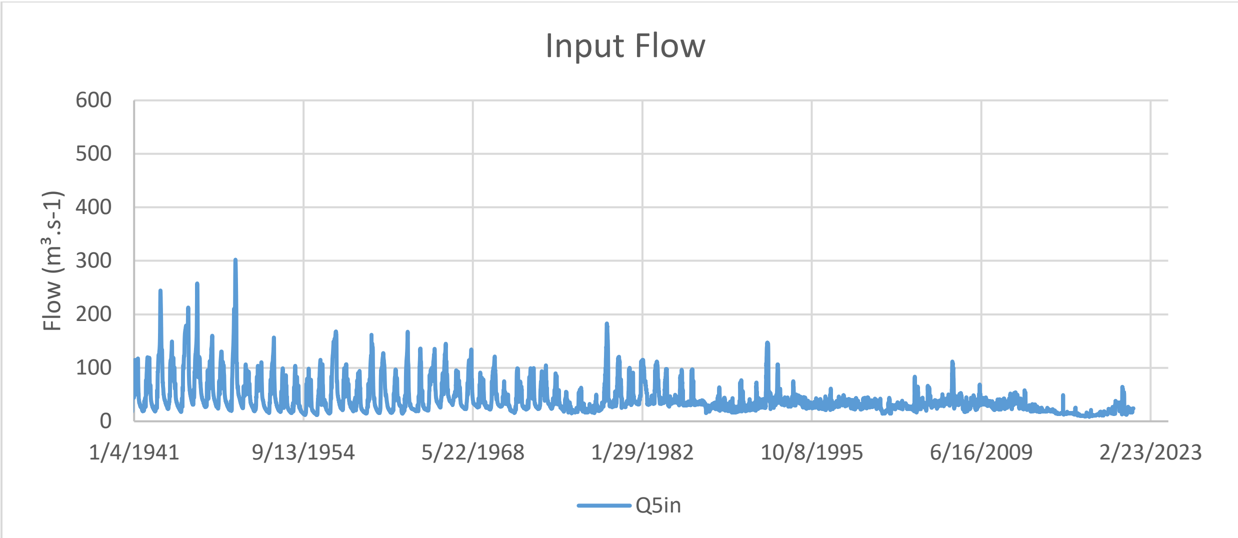
Supplementary Figure 2. Daily flow input for model application upstream of North Line water abstraction.



Supplementary Figure 3. Daily flow input for model application upstream of Itaparica Hydropower.



Supplementary Figure 4. Daily flow input for model application upstream of Paulo Afonso System Hydropower.



Supplementary Figure 5. Daily flow input for model application upstream of Xingó Hydropower.

3. Hydropower's Infrastructure Characteristics

The Supplementary Table 3 has the drainage area for each Hydropower Dam and the installed capacity to generate Hydroelectricity. In addition, the Supplementary Table 4 has the elevation – area – volume relation for the Hydropower Reservoirs. The turbine efficiency and the availability index are in the Supplementary Table 5. The average monthly evaporation for each reservoir are in the Supplementary Table 6.

Supplementary Table 3. Hydropower characteristics.

Hydropower	Drainage Area (km^2)	Installed Capacity (MW)
Sobradinho	498500	1,050
Itaparica	587000	1,500
Paulo Afonso system	599000	4,280
Xingó	608700	3,000

Supplementary Table 4. Reservoir Elevation-area-volume.

H. Sobradinho			H. Itaparica		
Elevation	Area (km^2)	Volume (M m^3)	Elevation	Area (km^2)	Volume (M m^3)
380.40	1,128,752	5,444	298.90	606,899	7,234,000
385.40	2,007,893	12,614	300.40	660,537	8,121,000
388.35	2,787,032	19,781	301.70	714,031	9,008,000
390.60	3,482,549	26,948	302.90	765,897	9,895,000
392.50	4,201,749	34,116	304.00	812,882	10,782,000
H. Paulo Afonso			**H. Xingó**		
Elevation	Area (km^2)	Volume (M m^3)	Elevation	Area (km^2)	Volume (M m^3)
251.50	213,000	1,373,000	138.00	60	3,800,000

Supplementary Table 5. Turbine efficiency and availability index.

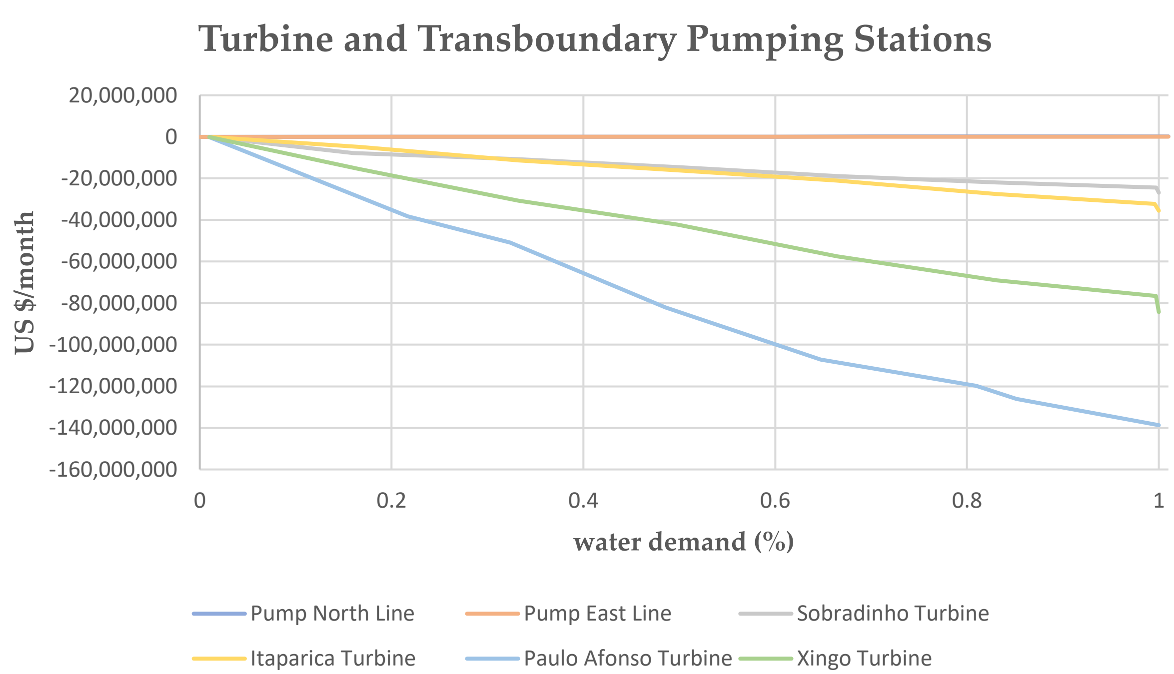
Hydropower	Turbine efficiency (%)	Availability index
Sobradinho	92.0	0.89
Itaparica	91.0	0.84
Paulo Afonso System	92.1	0.86
Xingó	93.0	0.86

Supplementary Table 6. Average Monthly evaporation for each reservoir (mm).

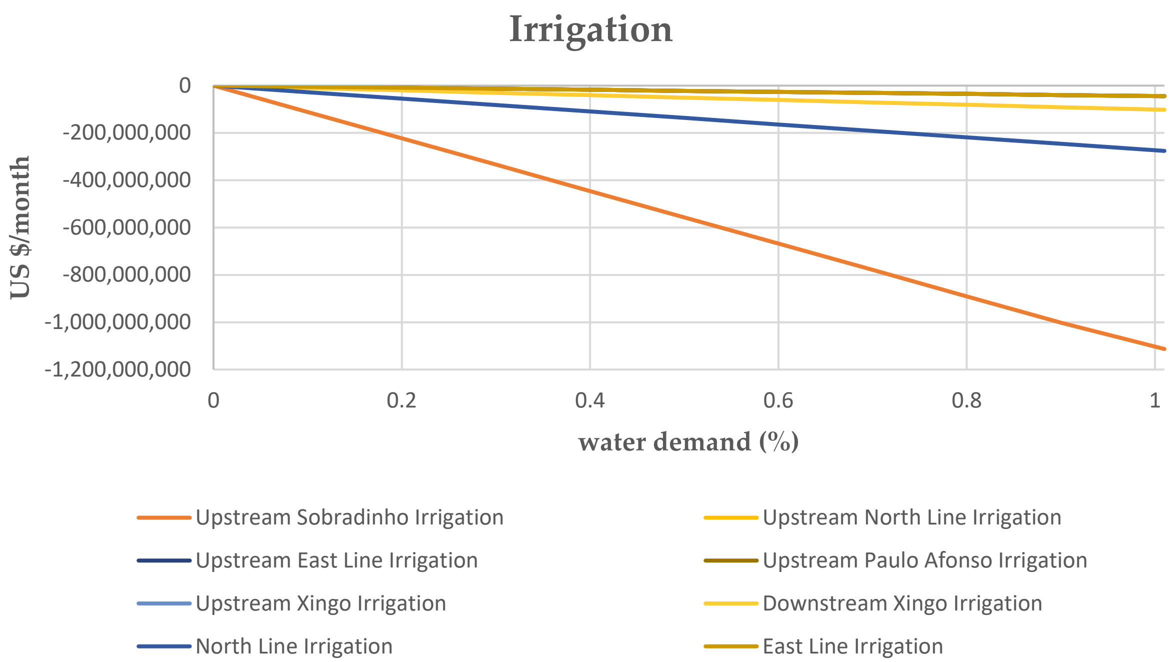
Month	Sobradinho	Itaparica	Paulo Afonso System	Xingó
Jan	118	140	140	140
Feb	106	109	109	109
Mar	81	81	81	81
Apr	132	105	105	105
May	153	109	109	109
Jun	142	101	101	101
Jul	158	123	123	123
Aug	181	158	158	158
Sep	197	180	180	180
Oct	189	195	195	195
Nov	114	158	158	158
Dec	98	152	152	152

4. Revenue Curves Constructed

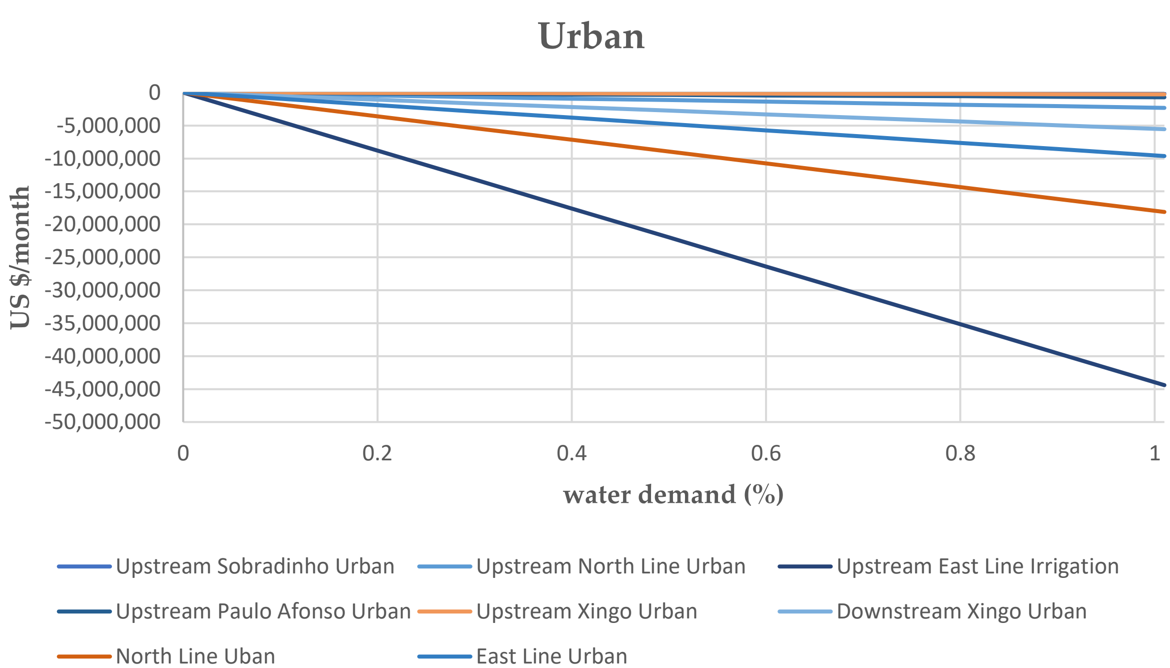
The revenue curves were constructed based on the proposed method present in the manuscript. Due to the optimization has a minimization objective function, the negative values represent the benefits, and for the pumping stations of SFTS the positive values represent a penalty due to the cost for water transposition. The Supplementary Figures 6 up to 9 presents the revenue curves for the model application.



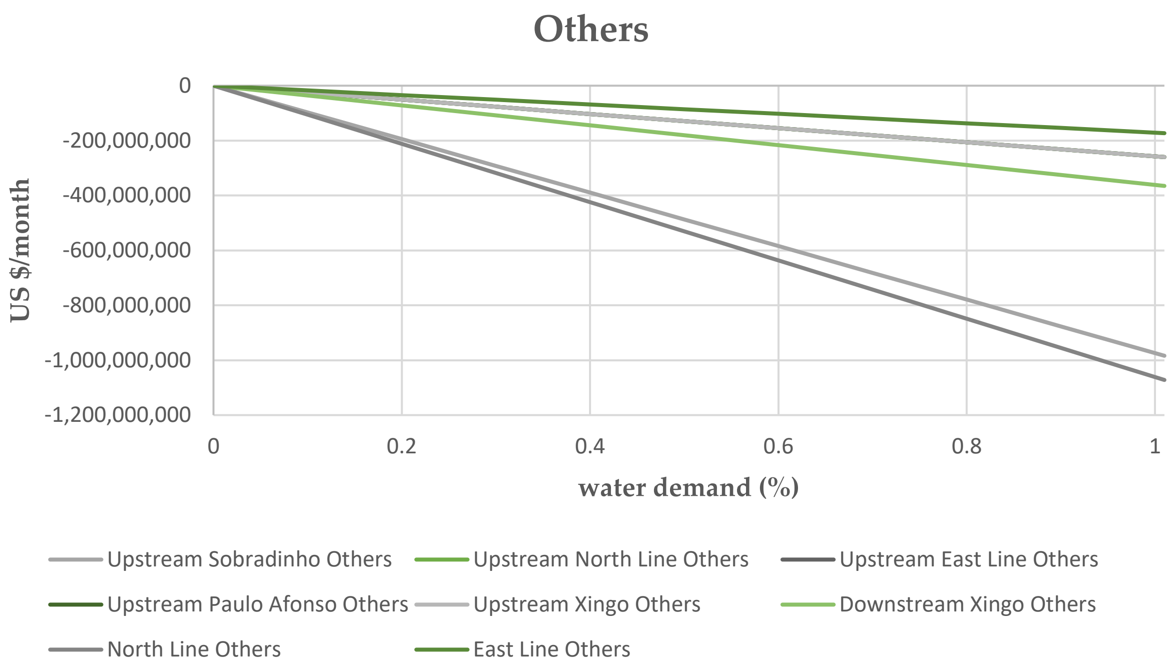
Supplementary Figure 6. Revenue curve for Hydropowers and Pumping Stations of SFTS.



Supplementary Figure 7. Revenue curve for Irrigation.



Supplementary Figure 8. Revenue curve for Urban supply.



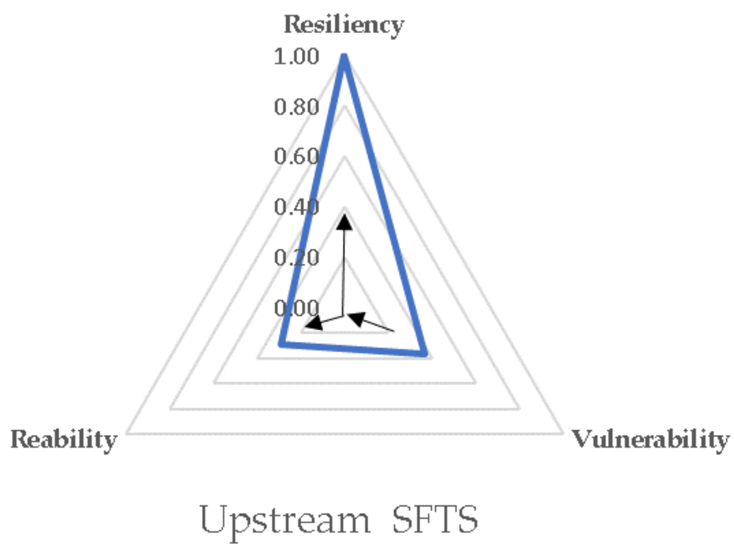
Supplementary Figure 9. Revenue curve for others water uses.

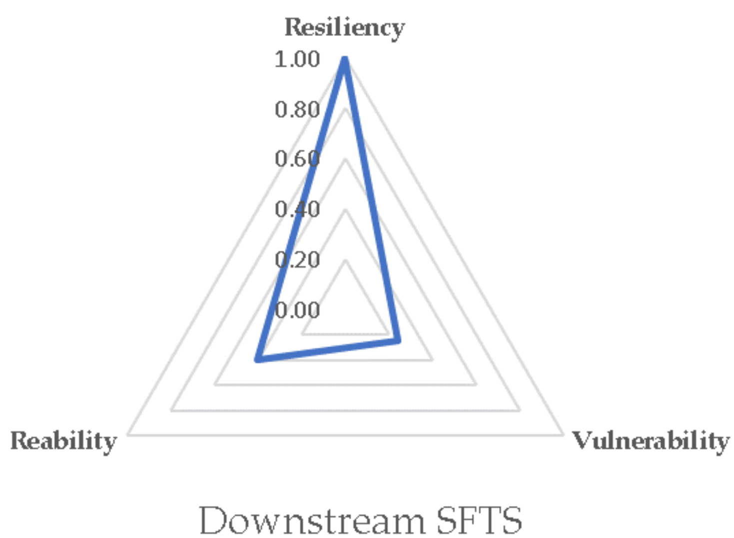
5. Supplementary Results

The supplementary results have the Sustainability index figures in more detail, and the hydrological alteration based on a hydrograph analysis.

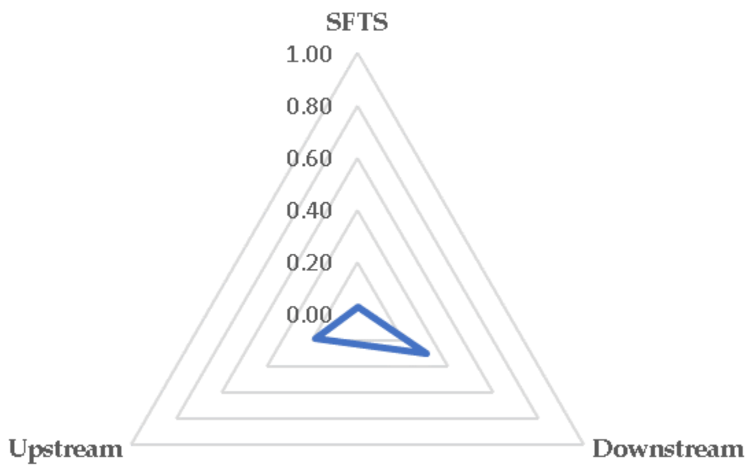
5.1. Sustainability

5.1.1. Priority-based optimization (2020)



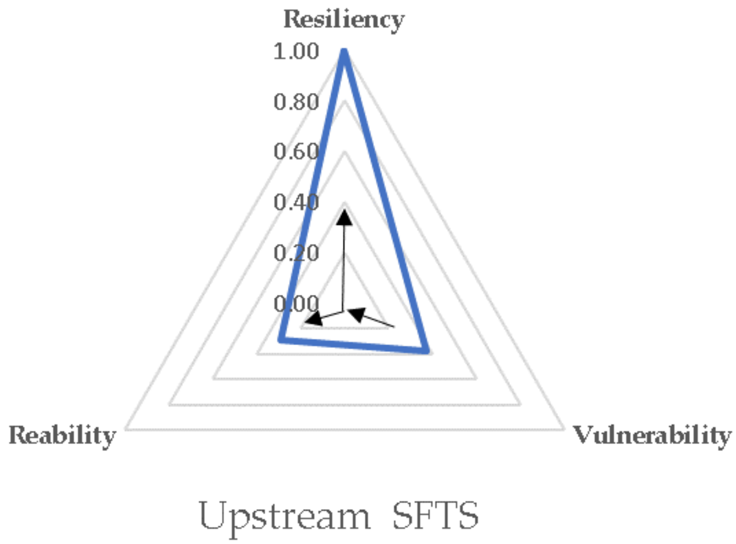


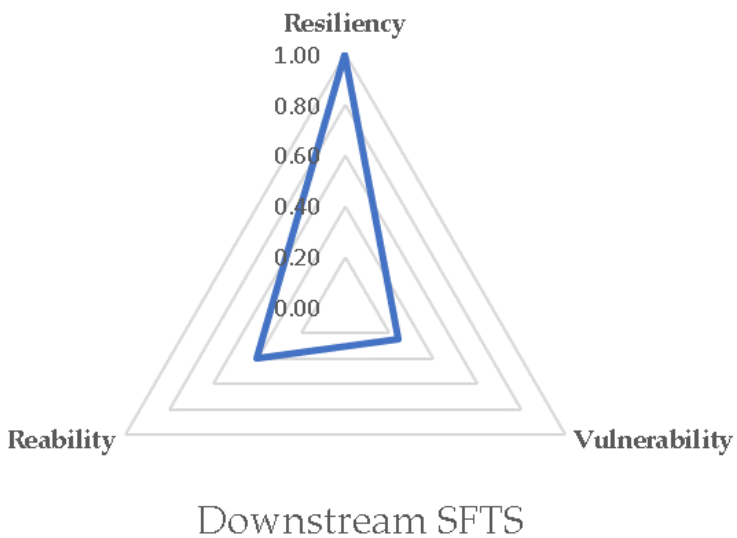
Transboundary Water Demand

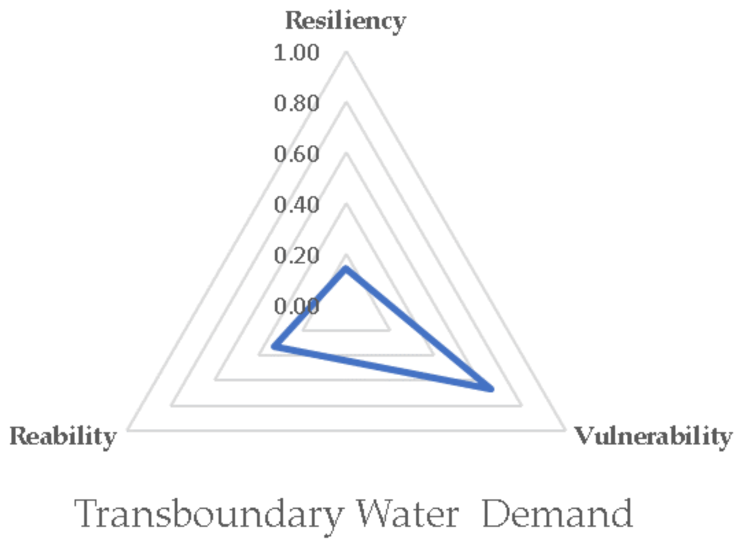


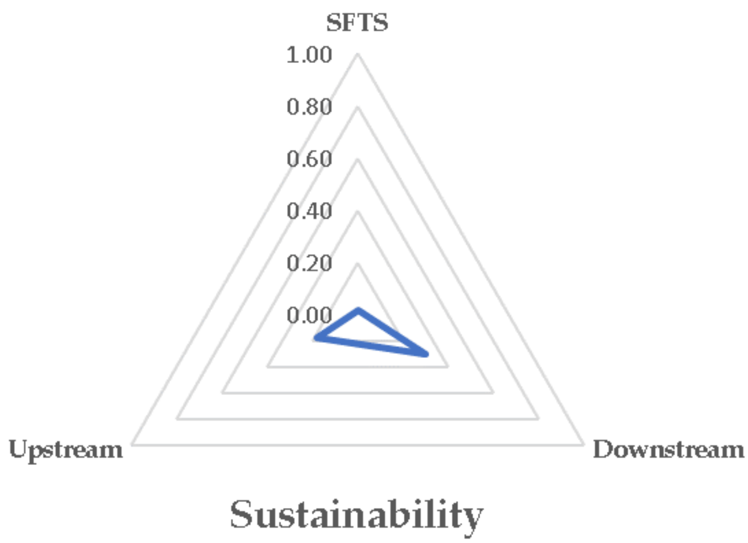
Sustainability

5.1.2. Priority-based optimization (2040)

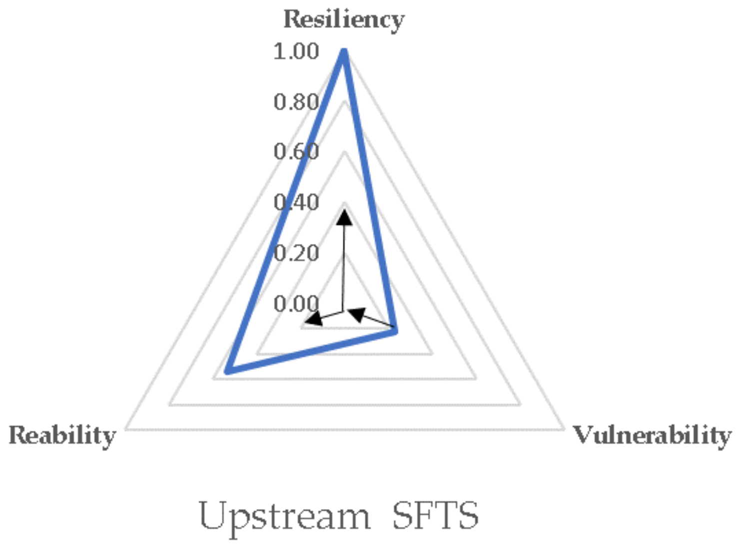


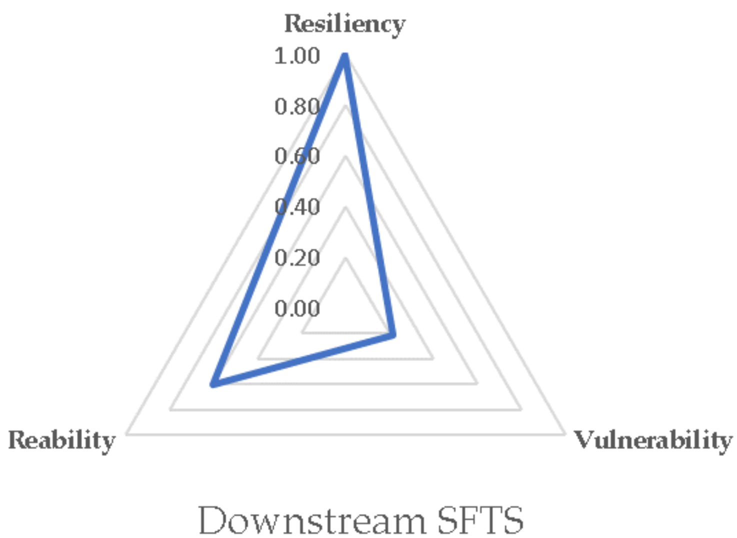


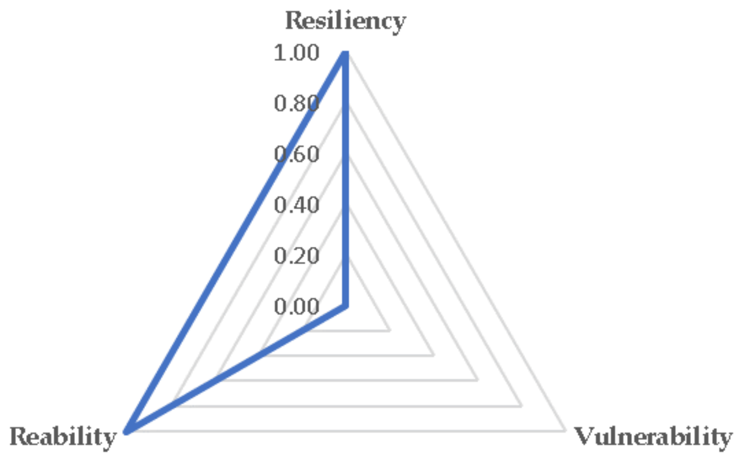

Resiliency
1.00
0.80
0.60
0.40
0.20
0.00
Reability
Vulnerability
Transboundary Water Demand


SFTS
1.00
0.80
0.60
0.40
0.20
0.00
Upstream
Downstream
Sustainability

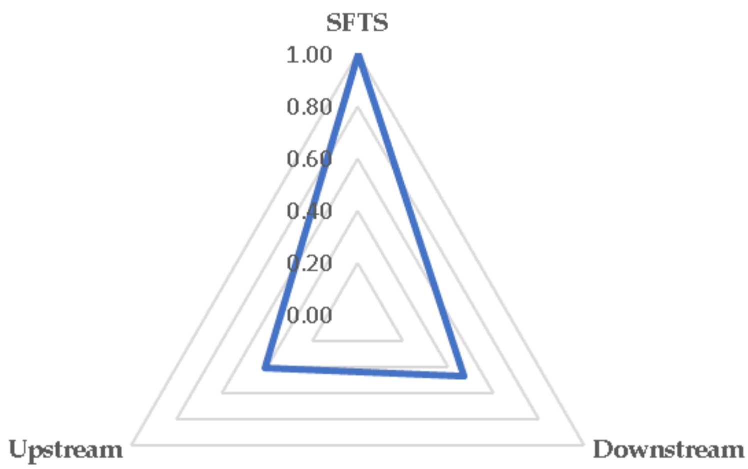
5.1.3. Hydro-economic optimization (2020)





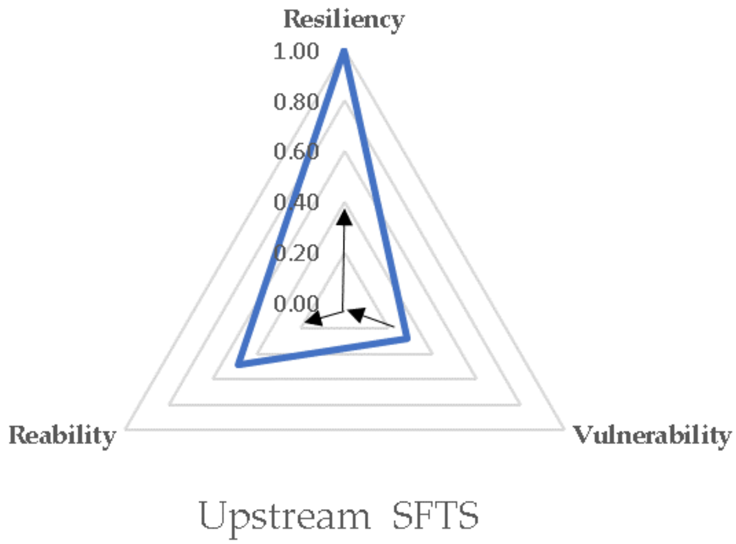


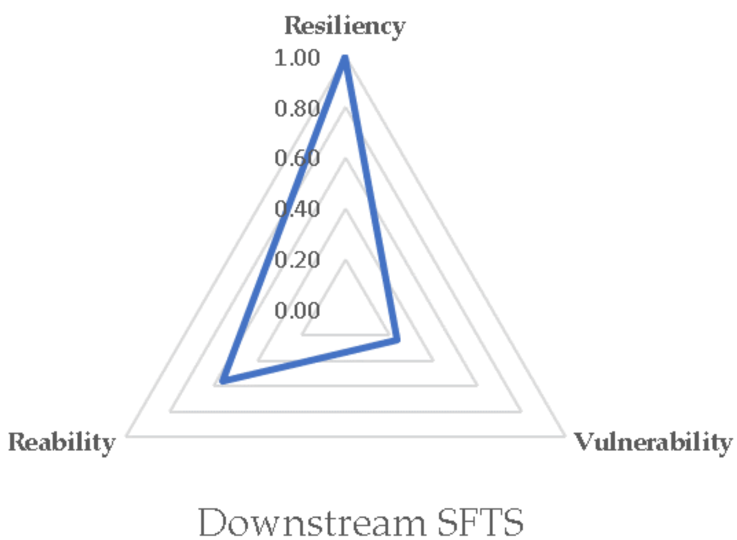
Transboundary Water Demand

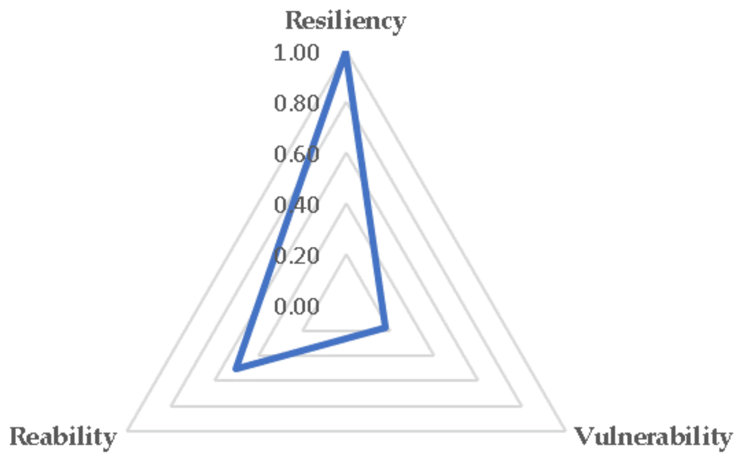


Sustainability

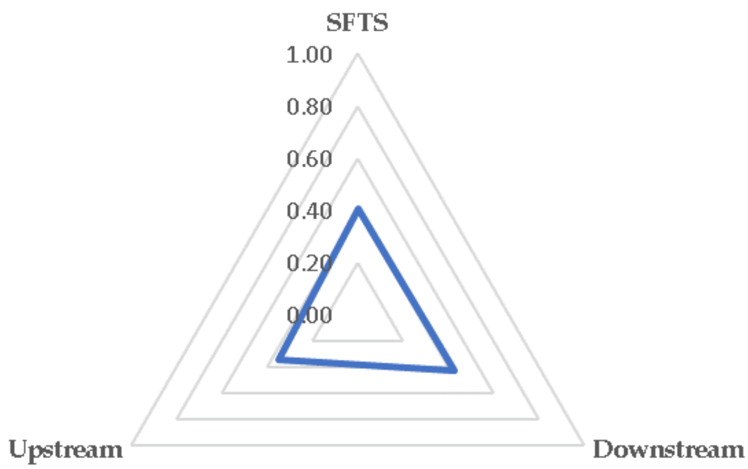
5.1.4. Hydro-economic optimization (2040)







Transbounday Water Demand

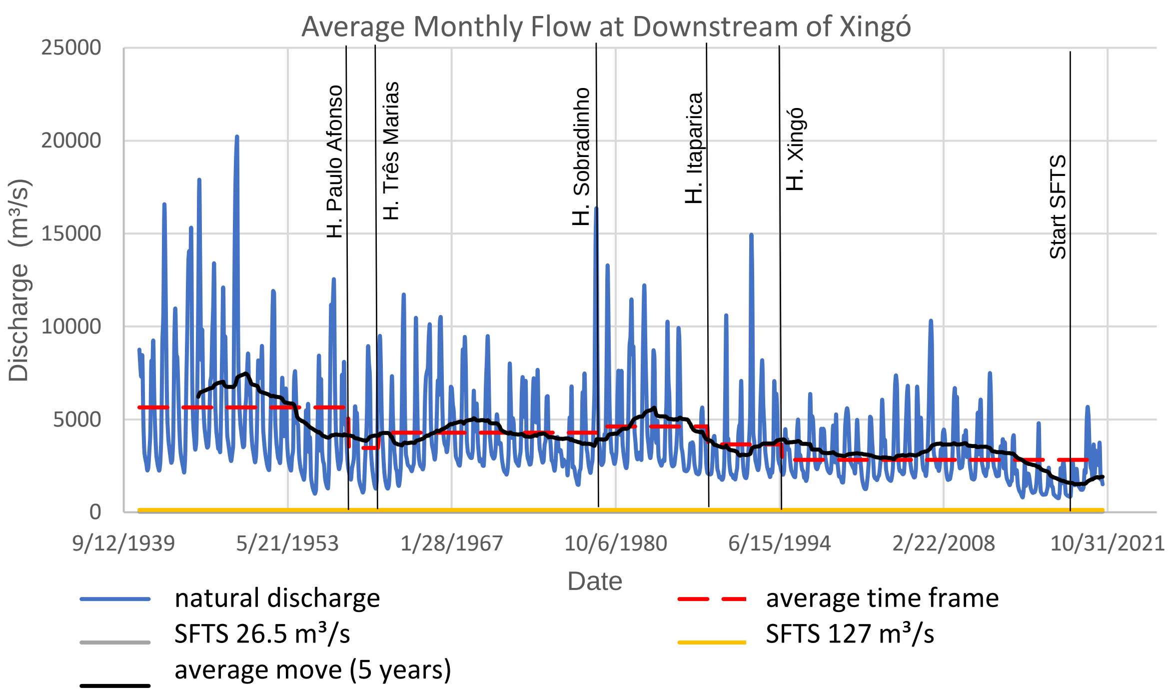


Sustainability

5.2. Hydrological Alteration

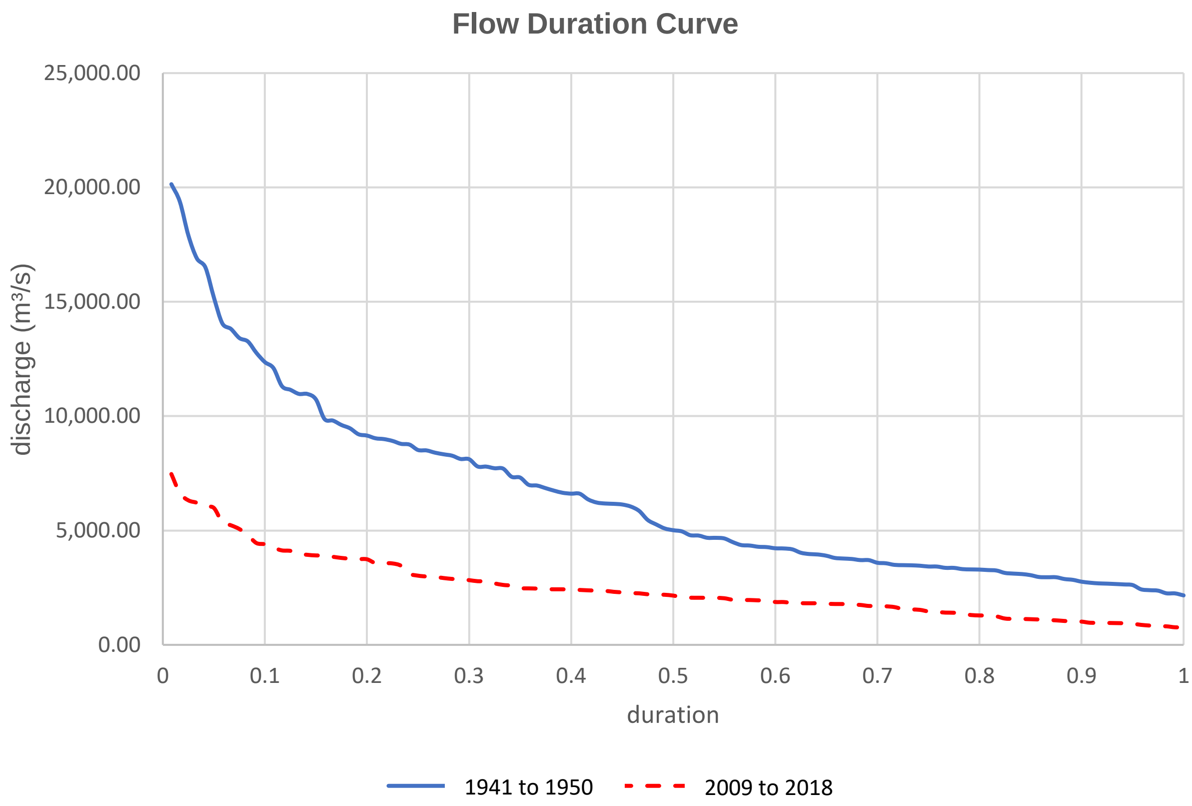
The São Francisco River has water infrastructure since 50's with the construction of Paulo Afonso system in 1952. Sobradinho was constructed in 1978, Tres Marias in 1961 (upstream dam from the model application), Itaparica in 1981, and Xingó in 1992. The dams and their reservoirs have presented a change in the hydrological regime with impact observed downstream of Xingó [41, 73].

Regarding the SFTS operation no impact on the hydrological index was significant (higher than 5%). The average discharge of SFTS is 3.25% of the minimal flow at downstream of Xingó (800 m³/s). The Supplementary Figure 10 presents the average monthly flow, move average with 5 years and the dam construction over the time. The average monthly flow before the first dam constructed was 5,000 m³/s, and after the construction of all dams was 2,600 m³/s.



Supplementary Figure 10. Average Monthly Flow at Downstream of Xingó Hydropower.

Selection the time frame of 10 years before the dams (1941 to 1950) and before the begin operation of SFTS (2009 to 2018) was observed a reduction of the total average flow. For the 50% flow duration was 59% of reduction and 90% flow duration the reduction was 67% (2,917 m³/s to 966 m³/s). Supplementary Figure 11 has the flow duration curve for the period of 1941 to 1950 and 2009 to 2018.



Supplementary Figure 11. Flow duration curve in 10 years' time frame.