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A New Approach for Evaluation of Water Reuse Opportunities in a Brazilian Thermoelectric Power Plant using the Water Sources Diagram Method

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ABSTRACT : *Currently, water scarcity is a problem that affects many countries.The wastewater reuse is a way to reduce the volume of effluent discharged by the industries.In view of this situation, water reuse has been demanded worldwide for environmental and economic reasons. This article deals with water reuse using Water Sources Diagram (WSD) based on a heuristic algorithmic tool applied to a thermoelectric plant located at Ceará State,in the northeastern of Brazil. The purpose of this paper is the new approach to the WSD procedure, which can divide its methodology in two steps: 1)application of the method considering tests with all the external sources of water stream, comparing the results for reduction of the freshwater consumption admitting multiple contaminants and fixed load and its subsequent analysis, based on contaminants concentrations data; 2)evaluation of the selected data set for the certification of WSD method. Several scenarios were tested and a 0.73% reduction in freshwater consumption was obtained without a regeneration process. However, for the nanofiltration and reverse osmosis membrane regeneration scenarios, reductions of 6.88% and 12.5%, respectively, were achieved. This indicates the advantage of using a regeneration process for water reuse. The variations observedin the freshwater consumption were less than 10%, according to subsequent analysis based on contaminants concentrations data, which indicate that the proposed verification methodology is appropriate and the data are considered valid to use for reuse.*

KEYWORDS *Nanofiltration, reverse osmosis, thermoelectric, water reuse, water sources diagram.*

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I. INTRODUCTION

The main applications of water in industry are related to its use as raw material, and can be incorporated into the final product; as auxiliary fluid, in the preparation of solutions, reagents and chemical compounds; for energy generation, transformation of energy accumulated in water into mechanical or electrical energy; as a fluid for cooling and heating systems, where demand is high, and also in sanitary facilities, washing equipment and in thermoelectric industries [1].

In order to maximize water reuse in industry, procedures have been proposed to calculate the minimum amount of freshwater consumption and to simultaneously synthesize the process water network.In the early 2000s, as a result of the improvement of the works of [2], [3], [4] and [5] an algorithm-heuristic methodology known as the Water Sources Diagram (WSD) was developed [6].

The WSD can be applied for determining maximum water reuse, with multiple external sources, multiple contaminants and for both reuse and recycle regeneration processes. In systems with multiple contaminants, the water network is generated from the selection of a reference contaminant and a reference operation, which allows the elaboration of the diagram and considers the simultaneous transfer ratio of contaminants [7].The WSD method has been applied in various industries to provide several flowsheet scenarios, which can be used for appropriate decision making, such as petrochemicals, textiles, oil refineries and pulp and paper [8]; [9]; [10]; [11].

WSD considers the mean value among the concentration of all contaminants in an External Source (ES) [12]. However, since its implementationto the same in its most recent enhancements [13]; [11],the method works with average concentration data in streams with multiple contaminants and no verification steps of the data used had been adopted in order to certify the reliability of the WSD method application.

In order to reach the water quality parameters for reuse, almost always requires effluent treatment by physical, chemical and eventually biological technologies. After the removal of contaminants, the effluent can be reused. In addition, a choice of one or a combination of two or more techniques may occurs, being determined by the potential of each technique and the mechanisms involved in reducing the specific contaminant [14].

The methodology proposed here inis applied to maximize water reuse,focusing on using the appropriate dataset, in a thermoelectric plant located in the semi-arid region of northeastern Brazil. The WSD method was combined with treatment technologiesin order to further improve the sensitivity of the method. The objective is that the scenarios generated as results will be able to provide industries with flexibility and precision for the reuse of waters and their respective regenerative processes.

II. MATERIAL AND METHODS

A new approach for WSD algorithm is proposed using the data from a thermoelectric plant and a reuse analysis of water streams is performed.

2.1 Methodology

The methodology consists of the following steps: (1) identification and data processing, (2) contaminants selection and pH calculation, (3) identification of external water sources (ES), (4) WSD method applicationand (5) evaluation of the selected data selected.

2.1.1 Identification and data processing

The water supply for this plant is from a weir where water availability depends on seasonality in this region. The plant operates with three cooling towers (concentration cycle 6) and boilers. Fig.1 shows the refrigeration and boiler streams system and the plant data that corresponds to a period of two years (February 2015 to February 2017).

The water collected in the weir passes through a filtration stage to remove coarse solids and stored in a tank (not shown in Fig.1), which provides make up water for the three cooling towers (TR01, TR02 and TR03). Their purges are destined for the final effluent tank. Besides weir, there are other five external sources: tanks (1) B65 and (2) B66, which remain exposed to climate changes and are supplied non-continuously by rainwater; their flows are also destined for the final effluent tank, (3) boiler blowdown (B60) and (4) the coal washing water (B74/75), which remains exposed to capture the water resulting from the washing of the coal courtyard and (5) a neutralizing tank. The treatment unit (TU), which is a coagulation-flocculation clarification treatment plant, receives water from (3), (4) and (5). After this step, the effluent is sent to a storage tank (Point B).

2.1.2 Contaminants selection

The selection of contaminants was based on the most harmful parameters for reuse in purges flow of the cooling tower, such as: ions, that contribute to alkalinity, hardness and corrosion of carbon steel material, such as silica (A), chloride (B), calcium (C), sulfate (D) and magnesium (E).

Calcium, chloride, magnesium, potassium, sodium and sulfate ions were determined from liquid chromatography analyzes using the Metrohm 930 Compact IC Flex 1 apparatus. The reactive silica parameter was determined according to the method provided in [15], using a spectrophotometer model HACH DR 2800.

In order to verify if the concentrations of the ions are in agreement with the operating standard established by the company, the same ions were analyzed in the Point B sink stream.

The pH parameter was determined by potentiometric method (4500-B) model Quimis.

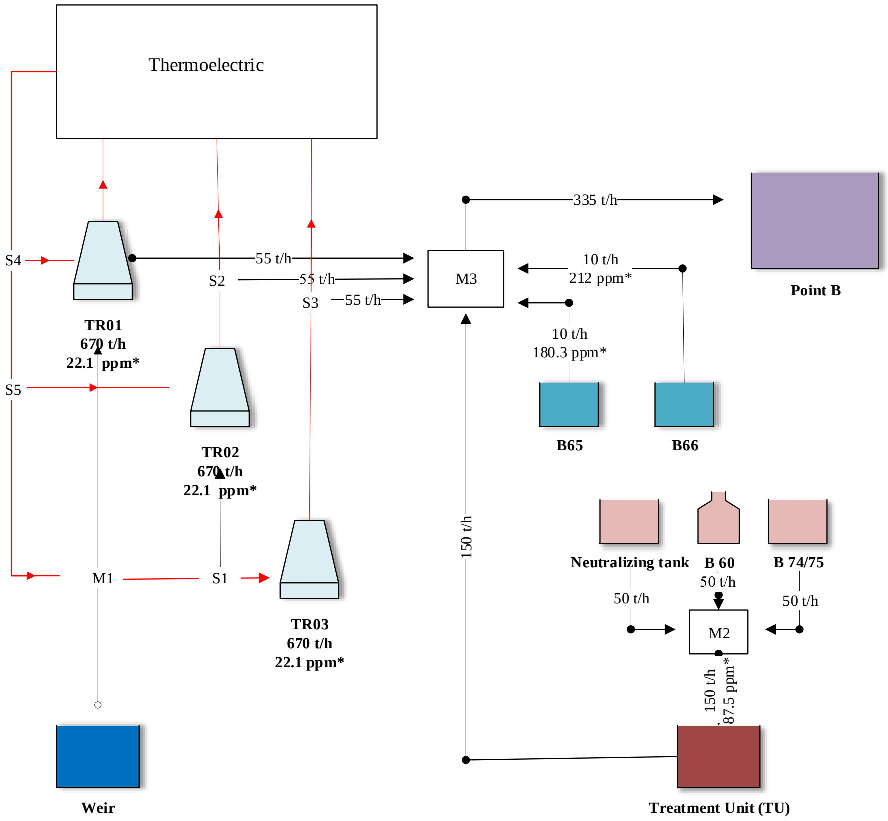

Fig. 1: Refrigeration system in the thermoelectric plant. (S) streams splitter; (M) streams mixer. * Mean contaminants concentrations for external sources considered to generate the WSD.

2.1.3 Identification of external water sources

The external water sources (ES) represent all available water supply for the plant. In this study four ES were considered: (ES 1) make up, (ES 2) TU, (ES 3) B65 and (ES 4) B66 and the selection criteria used to choose these sources were the highest flowrate and the highest water quality.

WSD considers the mean value among the concentration of all contaminants in an ES for each concentration cycle [12].

2.1.4 WSD Method

This method proposes the realignment of process streams in order to minimize the freshwater consumption. It has been improved over the years with numerous adaptations and enhancements, regarding the proposition of new algorithms to better deal with processes that present multiple contaminants [7]; [13]; [11] and better association of reuse with regeneration processes [14] in combined mathematical programming processes [16]; [17].

The concentration ranges are determined according to the inlet and outlet concentrations of each operation. The contaminant mass load transferred in each operation and concentration interval is represented in Equation (1).

$$\Delta m_{ki} = f_k * \left(C_{max,fi} - C_{max,ii}\right)(1)$$

where Δm_{ki} is the amount (mass load) of contaminant to be transferred in operation k, in the interval i; f_k is the flowrate of operation k; $C_{max,fi}$ is the maximum final concentration in the interval i; $C_{max,ii}$ is the maximum initial concentration in the interval i. Concentrations are measured in ppm. Complete calculations for the elaboration of the method can be observed in previous work [7].

2.1.5 Evaluation of data selected

This step aims to propose a methodology for verifying the adequacy of the data to be used in the WSD. Evaluation of methodology performing mean (MET) and minimum (MIT) concentration tests. In the conduction of the tests, the arithmetic means were initially calculated for each external source.

For the MTE, it was considered for all external sources, the mean concentrations of their respective contaminants. For the MIT, the external sources were tested individually. In the methodology, the ES selected was the one with the lowest concentration presented among its contaminants as reference. For the other external sources that compose the network, were considered the mean concentration data.
At the end, based on the reduction in freshwater consumption, the results obtained were compared for mean and minimum data from each scenario.

III. RESULTS AND DISCUSSION

3.1 Elaboration of scenario

Table 1 shows the selected contaminants and operations and their respective concentrations in each operation.

Table 1: Limiting contaminant concentration for operation.

Operation	f_k(t/h)	Contaminant	$C^{max}_{k,i,in}$ (ppm)	$C^{max}_{k,i,out}$ (ppm)	$\Delta m_{k,i}$ (kg/h)
TR01	670	A	4.62	27.75	15.49
		B	100.97	853.48	504.18
		C	1.48	62.96	41.19
		D	3.46	494.17	328.78
		E	0	136.05	91.15
TR02	670	A	4.62	27.75	15.49
		B	100.97	853.48	504.18
		C	1.48	62.96	41.19
		D	3.46	494.17	328.77
		E	0	136.05	91.15
TR03	670	A	4.62	27.75	15.49
		B	100.97	853.48	504.18
		C	1.48	62.96	41.19
		D	3.46	494.17	328.77
		E	0	136.05	91.15

where $C^{max}_{k,i,in}$ is the maximum initial concentration in the interval i,in operation k and $C^{max}_{k,i,out}$is the maximum final concentration in the interval i, in operation k.

3.1.1 Maximum reuse scenario without regeneration

Fig 2 shows theWSD based on the concentrations and flowrates of each operation, reported in Table 1. It describes the mass transfer in each interval and indicates the reuse streams.

The total freshwater consumption is 2,010 t/h. In addition to the need of 670 t/h of water for cooling towers 2 and 3, 14.70 t/h from ES 2 (7.35 t/h for each tower) is used. Only water from ES 1 and ES 2 were used. The WSD indicates a new freshwater consumption of 1,995.31 t/h, with a reuse of 14.70 t/h, representing a reduction of 0.73%. It should be noted that in this scenario the reused water already presents a level of contaminants that does not undergo any efficient treatment process in the removal of these elements. The water network with all the operations, external sources and the contaminant concentrations are shown in Fig. 3

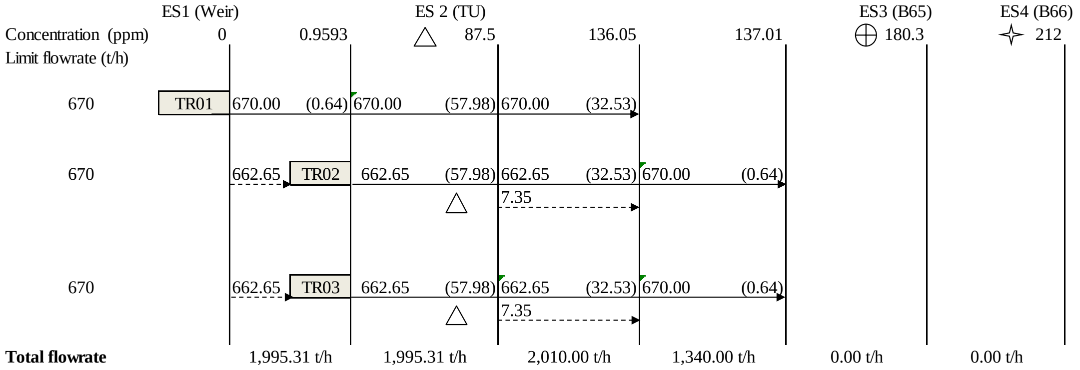

Figure 2: WSD for the maximum reuse scenario without regeneration.

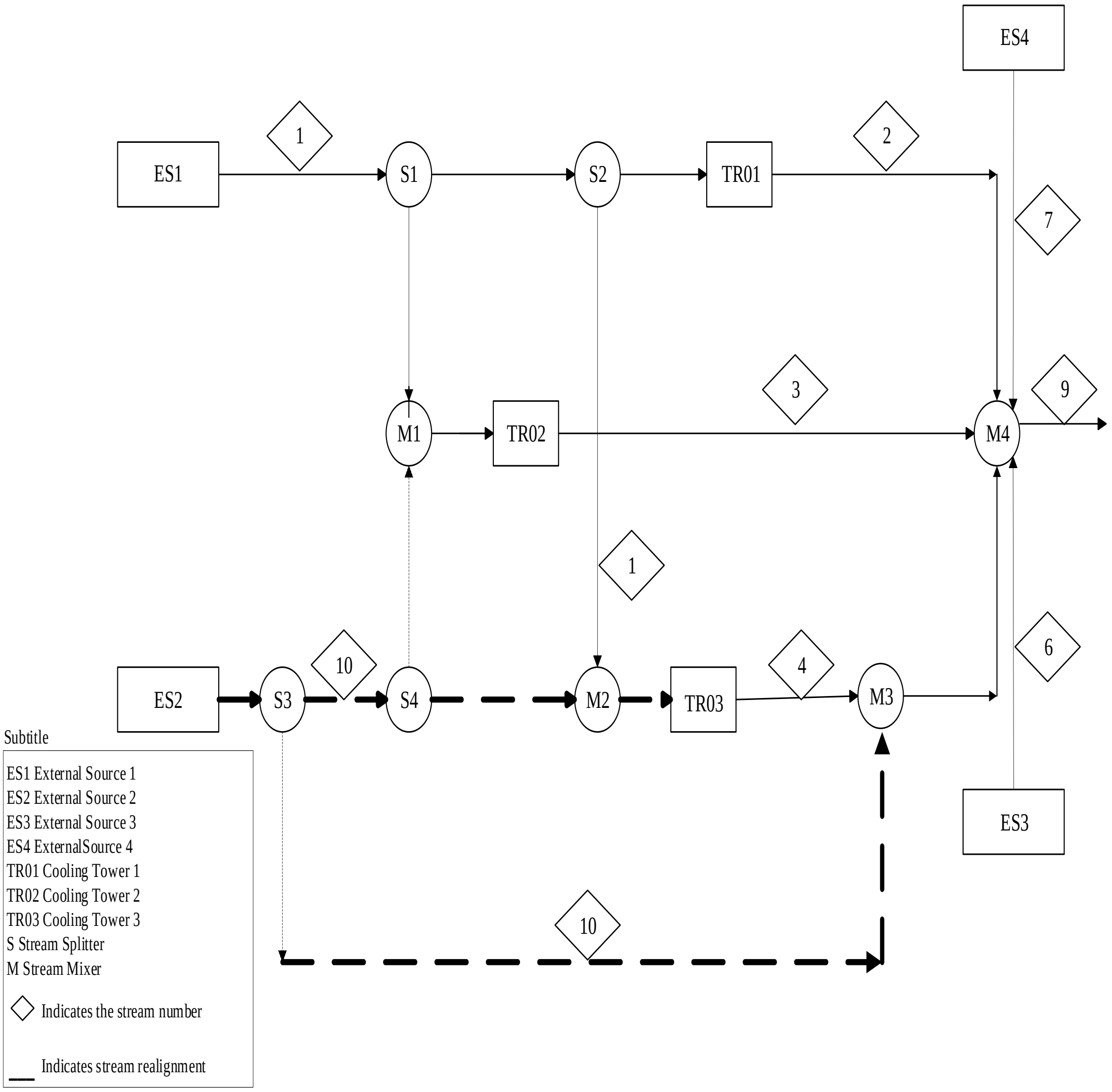

Figure 3: Water system network for maximum reuse scenario without regeneration

The final effluent needs to be treated, since its average concentrations exceed those established for reuse as a makeup of the cooling towers (22.1 ppm) reaching a value of 250.79 ppm to be disposed in natural water bodies, when the required standard is 127.5 ppm. In this case, one can note that stream realignment is possible, but not enough to reduce the freshwater consumption to thestablished limit. For this reason, to implement a regeneration process is necessary. The choice of this stream for treatment is due to the high flowrate presented by this stream, which contributes significantly to the reduction of freshwater consumption.
Table 2 represents the mass balance for the base scenario with no regeneration.

Table 2: Mass balance for base scenario maximum reuse without regeneration.

Stream number	1	2	3	4	5	6	7	8
Stream name	TR01	TR02	TR03	ES1	ES2	ES3	ES4	Point B
Flowrate (t/h)	55	55	55	1995.31	150	10	10	320.31
pH	8.38	8.38	8.38	8.11	7.53	7.81	8.7	7.78
Concentration (ppm)								
Silica	23.13	24.09	48.18	0	87.5	3.35	4.29	53.58
Chloride	752.51	753.47	1506.94	0	87.5	335.08	515.76	580.87
Calcium	61.48	62.44	124.88	0	87.5	165	114	88.39
Sulfate	490.71	491.67	983.34	0	87.5	392.94	366.24	398.2
Magnesium	136.05	137.01	274.02	0	87.5	5.33	59.73	132.93

3.1.2 Maximum reuse scenario with regeneration (Treatment Unit - TU)

The previous scenario was inefficient to reduce a large amount of freshwater. Thus, in order to attain the final effluent for direct reuse and/or disposal, it was decided to evaluate a scenario with the possibility of regeneration of the effluent. It can be done in a TU already installed in the plant. It also treats the effluent from B74/75 and B60 a. However, the treatment used at TU is only coagulation and flocculation process.

In this example, the TU will be used as a regenerator to treat the effluent from operation TR01 and after treatment, the effluent will be sent to a mixing point of streams TR02 and TR03, composing the final effluent.

The final concentration of the stream generated by the TU was fixed at 20 ppm, based on the average concentration of the plant's operating data from the beginning of its operation.

The final effluent concentration (191.83 ppm) is still higher than the needed for disposal (127.5 ppm), which indicates that the use of TU as a regenerator was not able to adjust the effluent for the disposal standards. Thus, other regeneration processes should be investigated.

3.1.3 Maximum reuse scenario with regeneration (Nanofiltration - NF)

The demand for a better water quality for reuse in cooling towers requires efficient treatments to remove contaminants, such as silica, calcium, chloride, magnesium and sulfate. Due to the low efficiency of TU, a new scenario was developed with a membrane regeneration that is a process well described in the literature as one of the main treatments for adequacy of effluents for reuse and/or disposal, meanly in cases where the higher water quality is required [18].

The NF process provides 251.5 t/h of water regenerated which 75% are treated effluent. In this case, although treated effluent presents low concentration of contaminants(average concentration 10.02 ppm) only 138.22 t/h is being used. This occurs because the concentrations of the contaminants in the TR02 and TR03 system do not exceed the allowed values (Table 1). Thus, the treated effluent and the recirculating flowrate must have their flowrates and concentrations predetermined and taken into consideration. Excess effluent can be stored and used as needed.

3.1.4 Maximum reuse scenario with regeneration (Reverse Osmosis - RO)

The reverse osmosis (RO) was used due its ability to retain low molar mass solutes, such as inorganic salts or small organic molecules.

The RO process provides 251.5 t/h (75% of the treated effluent) for the process. The low contaminants concentration of treated effluent(average concentration 3.24 ppm)allows all effluent to be reused and consequently decreases freshwater uptake.

The results for the RO processes were simulated based on the following removal efficiencies to chloride, calcium, sulfate and magnesium of 99.5%. For the NF processes the removal efficiencies to calcium and magnesium are 98.7%, to chloride is 95% and to sulfate is 96.7%. To the silica, removal efficiency is 89.2% in both process [19]; [20]. The Table 3 presents a comparison between the three types of regenerators tested.

Table 3: Regenerator efficiency comparison for final stream.

Final stream name	Point B	Point B	Permeate	
Regenerator	Without regeneration	TU	NF	RO
Flowrate (t/h)	320.31	280.00	138.22	251.25
pH	7.78	7.28	5.24	7.05
Concentration (ppm)				
Silica	53.58	20.20	5.79	5.79
Chloride	580.87	483.89	29.04	2.90
Calcium	88.39	51.58	1.14	5.41
Sulfate	398.20	327.94	13.14	1.99
Magnesium	132.93	75.56	0.98	0.99
Reduction in freshwater consumption (%)	0.73	3.20	6.88	12.50

After the regeneration step, it can be observed that the implementation of a regenerator (TU) contributed to reduce 4.57 times the freshwater uptake, when compared to the scenario without regeneration.

The regeneration by NF offers a reduction freshwater consumption approximately two times higher than the results achieved with coagulation/flocculation regeneration and approximately nine times higher than obtained without regeneration.While RO regeneration offers reduction approximately four times higher than the results achieved with coagulation/flocculation regeneration and seventeen times higher than obtained without regeneration.

3.2 Evaluation of the selected data and regeneration process

For a more assertive representation of their physical and chemical characteristics, it is necessary to ensure that the treatment data, used in the WSD method,is adequate in order to correctly express the most promising alternatives for stream realignment, reuse and/or recycle, reducing freshwater consumption.

In order to investigate the representativeness of mean values and minimum values of contaminant concentration were also tested for all external sources. The maximum values are not considered in the analysis because it would exceed the limit of the lowest concentration presented in the Table 4. By definition, when considering multiple contaminants, the WSD uses the mean concentration values of the contaminants presented in a stream. The minimum concentration for each stream is highlighted in bold in Table 4.

Table 4: Concentration values of contaminants from external sources.

Contaminant (ppm)	ES1 (Weir)	ES2 (B65)	ES3 (B66)	ES 4 (TE)
A – Silica	4.62	**3.35**	**4.29**	**19.63**
B – Chloride	100.97	335.08	515.76	294.09
C – Calcium	1.48	165	114	31.99
D – Sulfate	3.46	392.94	366.24	201.08
E – Magnesium	**0**	5.33	59.73	36.33

In the verification of the method, it will be used minimum values for the stream and the other contaminants will continue with their mean values. Therefore, each stream will be validated as to the use of its mean concentration data.

3.2.1 Minimal concentration of ES 1 (Weir)

For ES 1, the lowest concentration belongs to the contaminant magnesium (0 ppm), which will be applied for the other contaminants. For the other ES the mean contaminant concentrations were considered. The resulting diagram can be seen in Fig. 4.

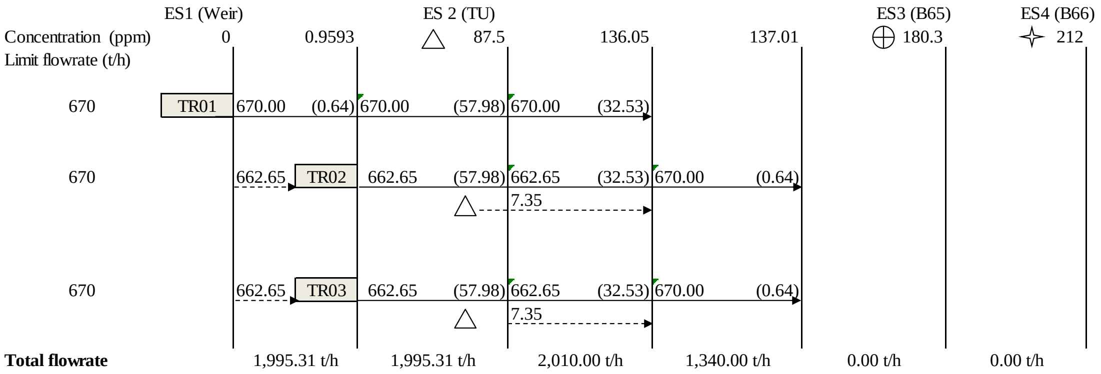

Figure 4: WSD for sensitivity analysis of ES 1 with concentration cycle 6.

The diagram shown in Fig. 4 indicates that the lowest consumption of freshwater was 1,995.31 t/h. The ES 2 was reused in the input of the cooling towers 2 and 3, which allowed a reduction of 0.7% in the consumption of the primary source. Fig. 5 shows the water network system.

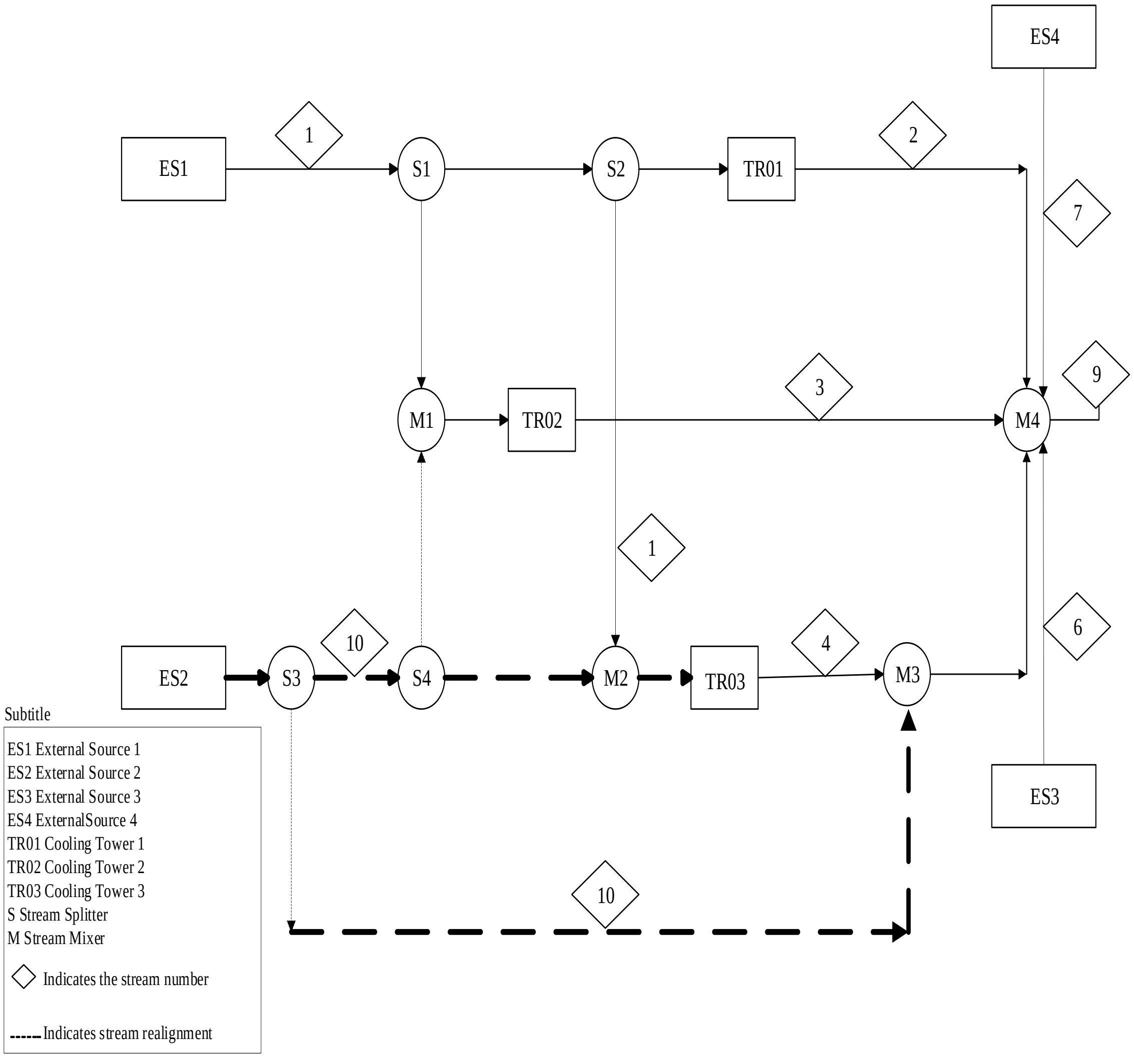

Figure 5: Water system structure for sensitivity analysis of ES 1.

Fig. 5 shows the use of ES 1 and ES 2 in the initial water supply and the contribution of external sources 3 and 4 in the composition of the final effluent. The use of these ES in the final effluent aims to minimize contaminants concentration and the harmful effects on the environment. However, even after the addition of the streams, the maximum values of the concentrations established for disposal were not reached, as well as the concentrations required for stream reuse.

3.2.2 Minimal concentration of ES 3 (B65)

For the ES 3 the lowest concentration belongs to the silica contaminant (3.35 ppm), so the mean value for this source was considered 3.35 ppm for all its contaminants and the other sources were represented with average values of concentration. The resulting diagram can be seen in Fig. 6.

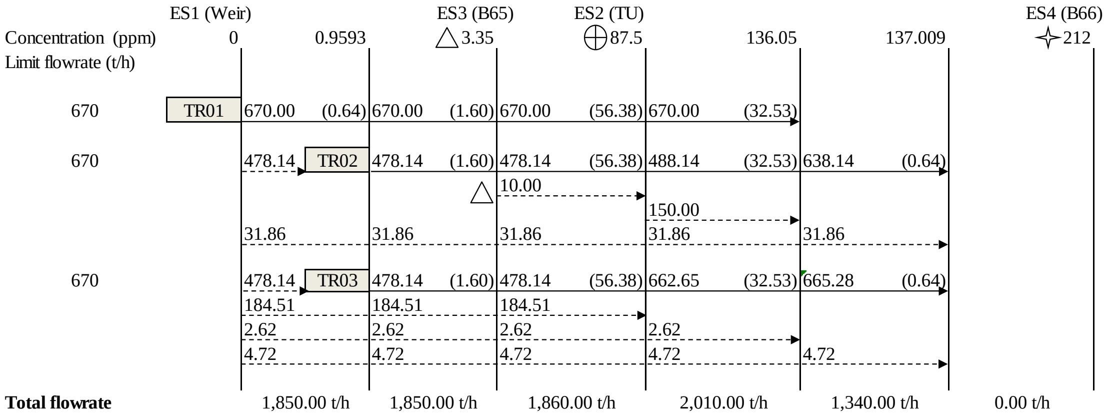

Figure 6:WSD for sensitivity analysis of ES 3.

The diagram indicates that the lowest consumption of freshwater was 1,850.00 t/h. The ES 3 was reused to the cooling tower 2, which allowed a reduction of approximately 8% in the consumption of the primary source. Fig. 7 shows the correspondent water network system.

3.2.3 Minimal concentration of ES 4 (B66)

The Fig. 8 shows the use of external sources 1, 2 and 3 in the initial water supply and the contribution of ES 4 in the final effluent composition. However, in this case a concentration violation is observed at the inlet of TR02, which makes its use unfeasible. And again, in order to minimize the concentration of contaminants and the harmful effects on the environment resulting from the concentration of contaminants throughout the process, the use of ES 4 in the final effluent was not able to reach values established by company for disposal.

For this diagram, the lowest consumption of freshwater was 1,850.00 t/h. ES 4 was used to complement the water stream to the cooling tower 2 and ES 2 was used to complement the water stream to the cooling tower 2. This configuration allowed a reduction of approximately 8% in consumption of the primary source. Fig. 9 shows the water network system.

The Fig. 9 shows the use of external sources 1, 2 and 4 in the initial water supply and the contribution of ES 3 in the final effluent composition. However, in this case a violation in the concentration is observed at the inlet of TR02, which makes its use unfeasible. The use of ES 3 in the final effluent was not able to minimize harmful effects on the environment and concentration of contaminants to reach values set by the company for disposal.

3.2.4 Minimal concentration of ES 2 (TE)

For ES 2 the lowest concentration belongs to the silica contaminant (19.63 ppm). Therefore, the average for this source was considered 19.63 ppm for all its contaminants and the other sources continued with average values of concentration. The resulting diagram can be seen in Fig. 7

In this case, the lowest freshwater consumption is 1,944.52 t/h. The ES 2 was used to complement the cooling streams 2 and 3 cooling towers, which allowed a reduction of approximately 3.3% in primary source consumption. The water network system can be seen in Fig. 8

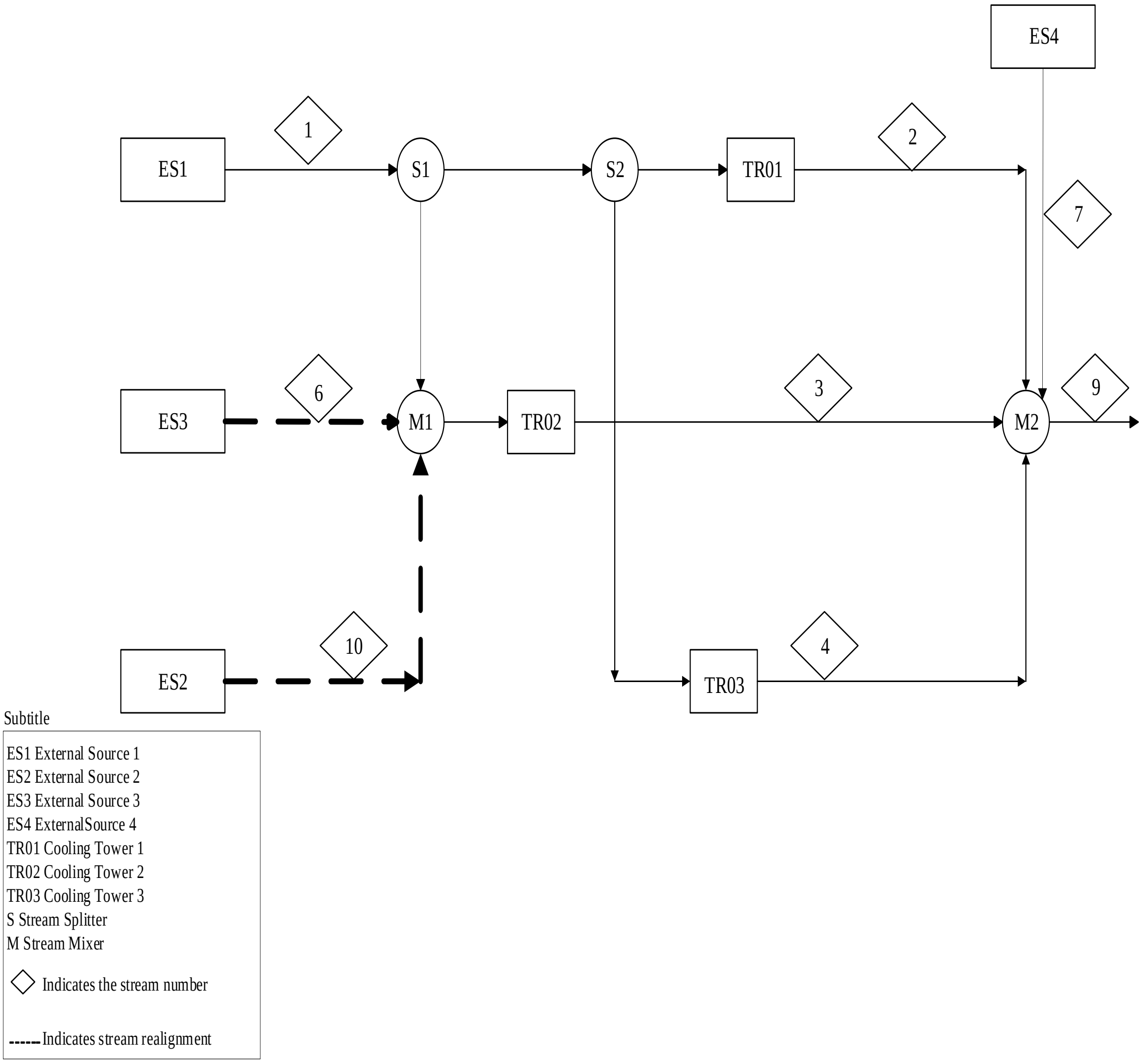

Figure 7: Water network system for sensitivity analysis of ES 3.

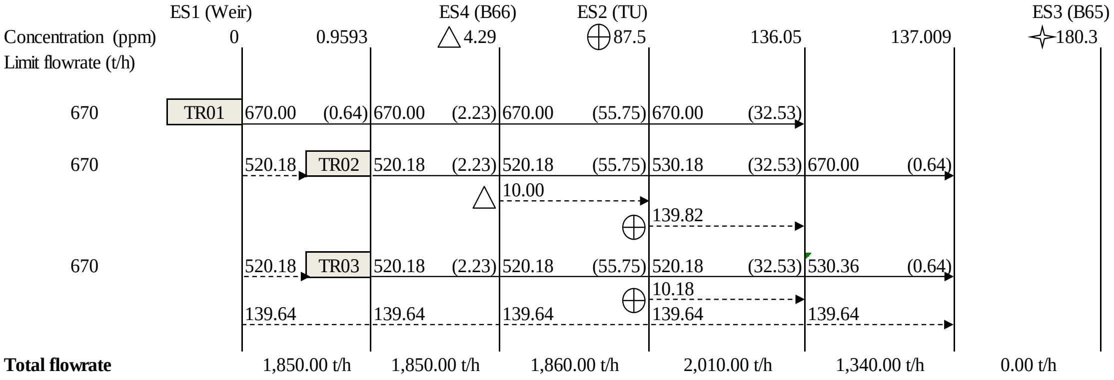

Figure 8: WSD for sensitivity analysis of ES 4.

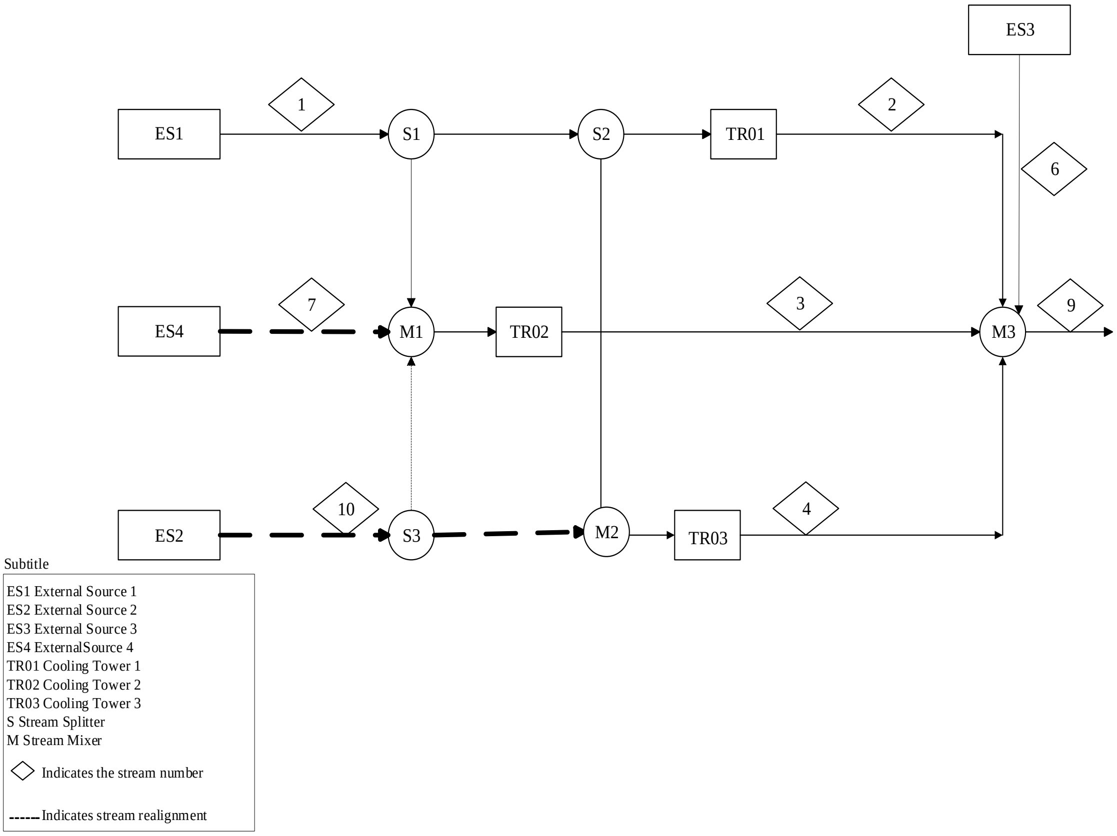

Figure 9: Water network system for sensitivity analysis of ES 4

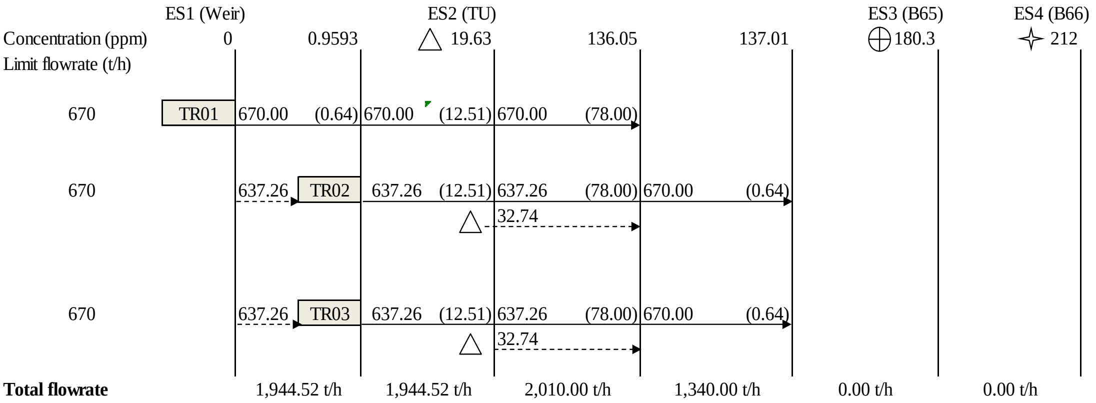

Figure10: WSD for sensitivity analysis of ES 2.

Fig. 11 shows the use of external sources 1 and 2 in the initial water supply and the contribution of external sources 3 and 4 in the final effluent composition. The use of these ES in the final effluent aims to minimize harmful effects, resulting from the concentration of contaminants throughout the entire process. However, even after the addition of the streams, the values established for disposal were not reached, as well as the concentrations necessary for stream reuse.

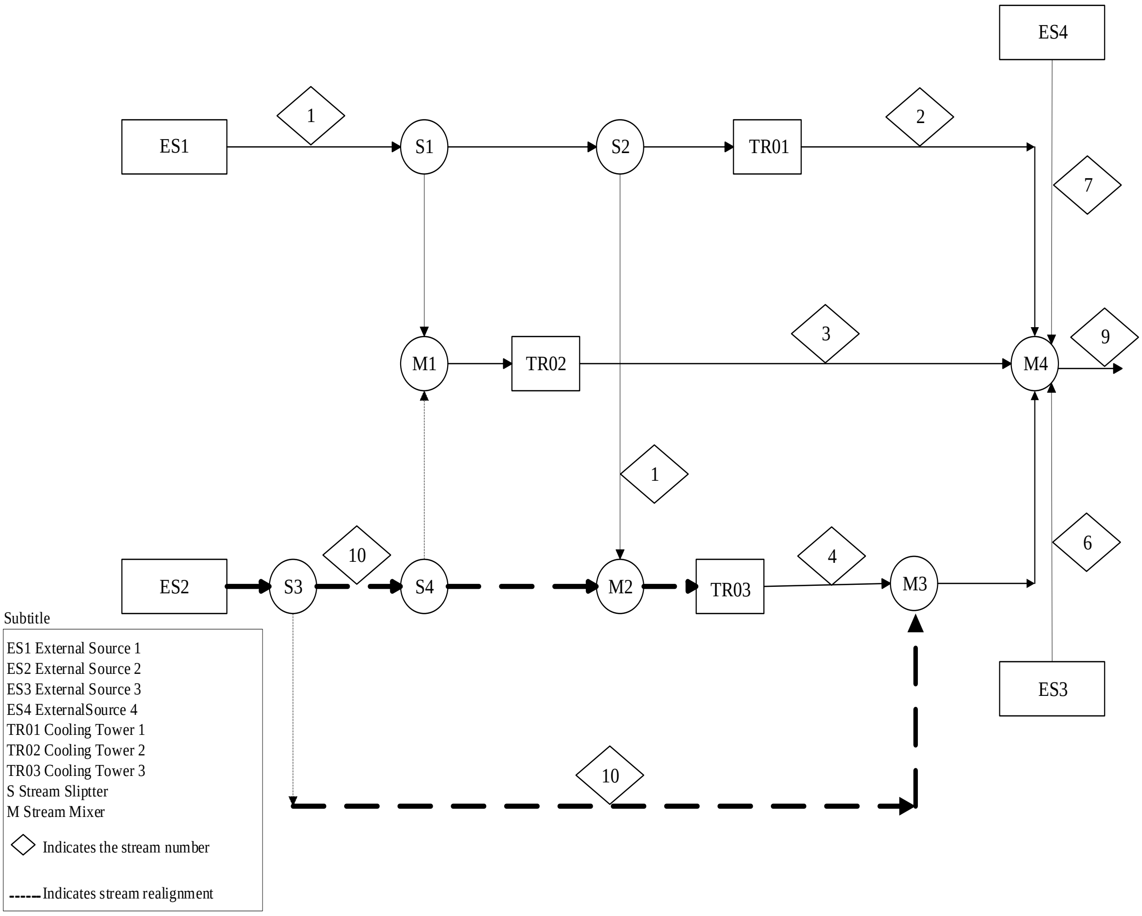

Figure 11: Water network system for sensitivity analysis of ES 2

3.2.5 Minimal concentration of all external sources with all contaminants

In this analysis were used minimum value of contaminants concentration for all external sources. The resulting diagram can be seen in Fig.12.

The scenario presents the lowest consumption of freshwater (1,840.00 t/h). All external sources were used during the process, which allowed a reduction of approximately 8.5% in primary source consumption. Fig. 13 shows the water network system

The analysis of the ES in the tests proposed by the methodology verification revealed that the use of all the ES in their minimum concentrations presents the highest economy in terms of freshwater consumption. Thus, this would be the most appropriate scenario for adoption by the company in case of water scarcity. The Fig.14 expresses a comparative of the concentration variation as a function of the total minimum water consumption and the reduction in freshwater catchment and effluent discharge flowrates by the NF and RO processes.

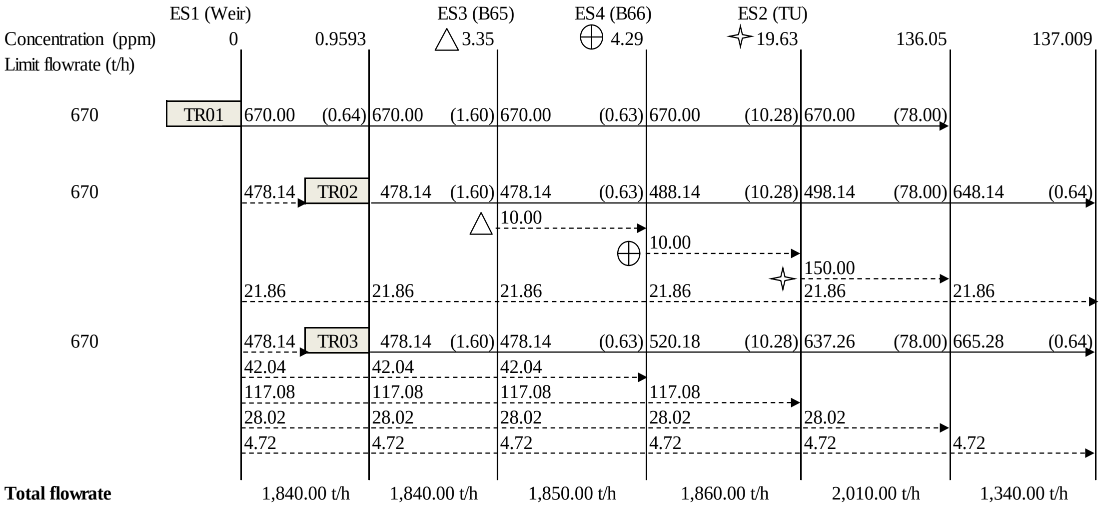

Figure 12: Diagram for sensitivity analysis of all ES.

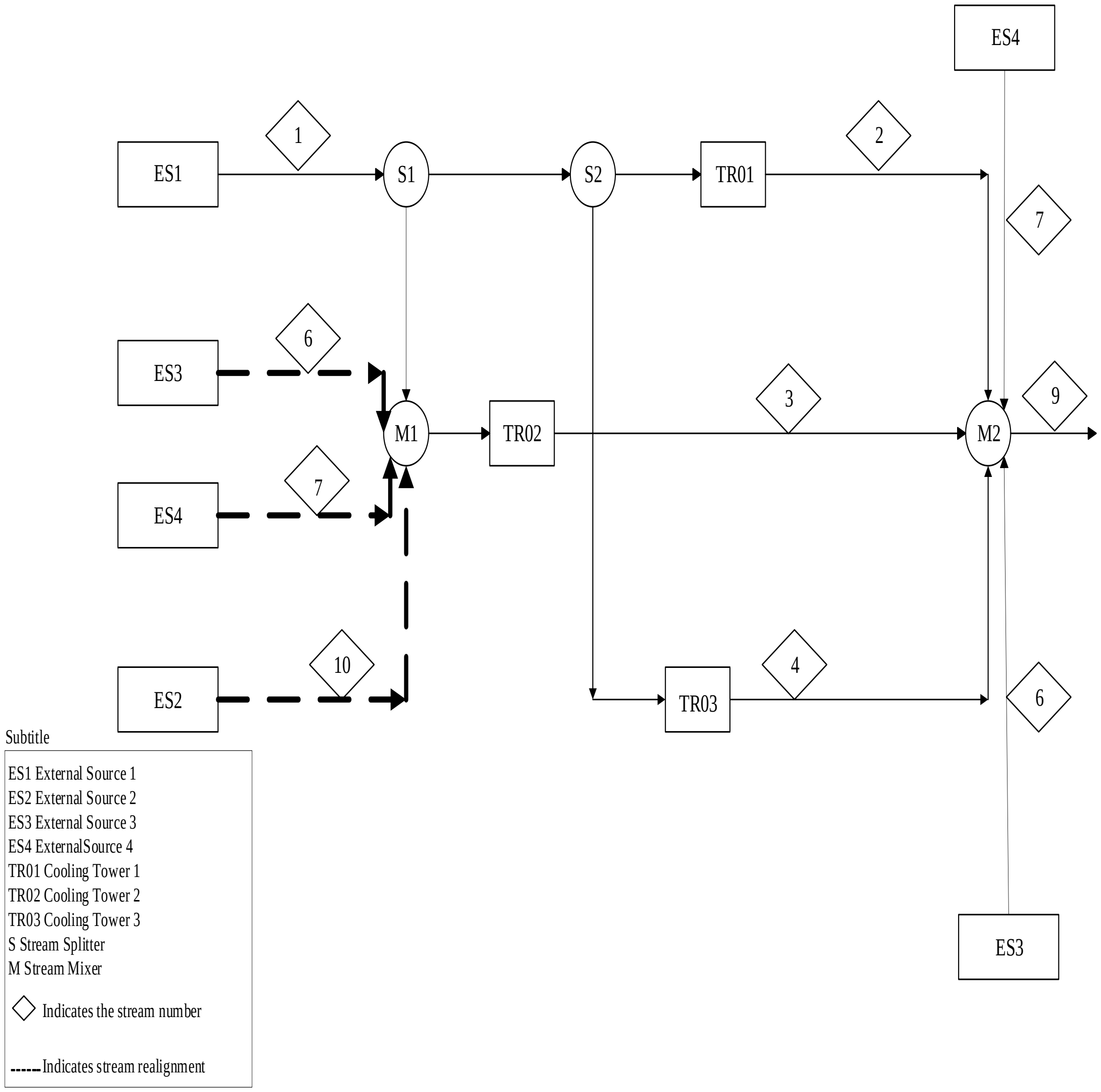

Figure 13: Water network system for sensitivity analysis of all ES.

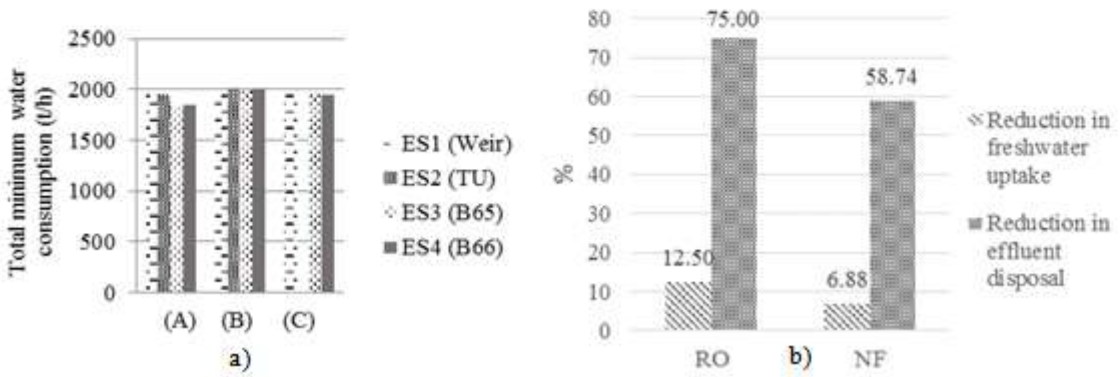

Figure 14: a) Variation of the minimum total freshwater consumption for minimum and average data. (A) Scenario with minimum concentration data for all ES; (B) Scenario with mean values of concentration for all ES, without regeneration; (C) Scenario with average data with regenerator (TU). b) Reduction of freshwater consumption and effluent disposal with regeneration with NF and RO membrane processes.

It is worth mentioning that the last set of data does not present the stream ES2, because TU, regenerates it and, acting as a regenerator of the stream TR01.

A variation in freshwater consumption of less than 10% (0.7% to 8.5%) is observed when comparing the results of each ES generated scenario, which suggests that the use of mean contaminant concentration data is representative.

The cost of dam water availability for the plant is \$ 1.05/m^3, and the cost for the disposal of effluent is \$ 1.48/m^3. The energy required for the process is produced by the plant itself, so the cost of energy is not considered.

It can be seen that besides producing better water quality by reverse osmosis also provides better freshwater uptake savings than nanofiltration and no pH adjustment is required which means a reduction in chemical reagent costs. Therefore, all treated effluent by reverse osmosis will be reused directly while by NF, part of the volume should be stocked to later use and does not contribute to reduces water consumption.

Reductions of 16% in freshwater water uptake and 49% in wastewater disposal were achieved by treating effluents from cooling systems through membrane nanofiltration [21].

The NF process represents a water uptake savings of 99,518.40 m^3/month and \$ 104,233.70/month while the RO process represents a water uptake savings of 180,900.00 m^3/month and \$ 189,471.30/month. For the both process the wastewater disposal savings was \$ 180,900.00 m^3/month and \$ 267,966.60/month.

IV. CONCLUSION

The use of Water Sources Diagram method showed that the variations observed in the percentage of freshwater consumption for scenarios with minimum and mean data was less than 10%. This means that the use of the average of concentrations values can be considered representative for the elaboration of reuse alternatives.

The regeneration with TU only was not enough to allow the effluent for reuse and / or disposal. However, membrane regeneration processes are able to adjust effluent to the appropriate quality standard for reuse and to reinforce the importance of the appropriate selection of the regeneration process.

The reduction of freshwater consumption for the scenario using NF was 6.88%; 12.5% for the scenario with RO; and, 0.73% for the scenario with no regeneration. NF is an efficient process;however, the pH parameter value indicates the need for chemical adjustments, which the RO does not require. Moreover, RO produce water with less salts concentration than NF that allows for freshwater uptake savings and makes the RO process more useful.

The reduction in effluent disposal occurs for both NF and RO in the order of to \$ 180,000.00 m^3/month and \$ 267,000.00 m^3/month, respectively.

The adaptation of WSD in the methodology proposed in this work was important to achieve a reduction in freshwater consumption of a thermoelectric plant. Its combination with a proper regeneration process demonstrated to be a good alternative, not only to maximize reuse, but also for a better effluent disposal. Furthermore, the adoption of the data treatment procedure proposed in this paper ensured higher reliability for the use of the tool and established a method for its use.

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