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Management of Water Consumption in Pulp and Paper Industry – A Case Study using Water Sources Diagram

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In the present work a brief literature review focusing the analysis of water systems in the pulp and paper industry is presented and the Water Sources Diagram (WSD) method is applied in a case study. This algorithmic procedure emerged as a viable alternative to minimize the water consumption in process plants, including the pulp and paper industry, and its robustness allows dealing with large-scale problems in the presence of multiples contaminants. The procedure also allows to obtain simultaneously the network structure and the minimum fresh water consumption target. WSD rules to achieve minimum consumption are (Gomes et al., 2007): (1) Use external water sources only when internal water sources are not available, (2) Transfer all the possible amount of contaminant inside a concentration interval and (3) For operations those are present in more than one interval, the stream must continue to flow through the same operation until its end. This last heuristic avoids the division of operations. The WSD methodology is here applied in the bleaching section and focuses the minimization of water consumption through maximum reuse. Three washers compose the bleaching section: Chlorine washer, Alkali washer and Hypo washer. According to original data (Shukla et al., 2012) the bleaching section requires 8,628 m^3/d of fresh water and generates 5,097 m^3/d of wastewater without integration. Applying the WSD methodology the total fresh water requirement decreased to 5,085.51 t/d and the total wastewater generation is 1,548.52 t/d; 846.21 t/d from the chlorine washer, 642 t/d from the hypo stage washer and 60.31 t/d from the alkali washer. Therefore the WSD indicates a possibility of 41 % reduction in fresh water consumption and 69.61% reduction in wastewater generation. The comparison among the WSD results and the results of Shukla et al. (2012), for the same problem, could not be made because it was identified an violation in COD contaminant concentration in the alkali washer in the results of these authors.
The WSD methodology has shown to be an important tool when it's desired to set new alternatives for water reuse in a systematic and efficient manner, such as in programs of water resource management in the industry.

1. Introduction

Water is a natural resource commonly used in the process industry. Chemical and petrochemical plants, petroleum refineries and pulp and paper industries use a large amount of water. The water used in these plants is directly connected to the effluent generation (water plus contaminants), which must return to the environmental. The pulp and paper industry is a major consumer of water in industry, and generates wastewater with high concentration of COD (chemical oxygen demand) and suspended solids, providing high pollutant loads. Water resources management requires planning the efficient use of water in paper manufacturing, involving washer filters, bleaching, liquors clarification, cooling towers and boilers.
Nowadays, the conjuncture of water scarcity, restricted environmental laws and rising costs of energy and effluent treatment have guided the industries to adopt strategies of water management. The area of Process Integration allows developing and applying methodologies for process optimization, focusing the reduction of the water consumption and of the environmental impacts related with these activities. The

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practice of water and wastewater reuse is an important option for the water resources management in the industry, aiming to reduce their water consumption and hence their effluent generation.
The present aims to show a brief survey of recent studies on water consumption in the pulp and paper industry and to demonstrate the application of the Water Sources Diagram in one of them.
Substantial opportunities for water consumption savings have been identified in the water system of a Kraft pulp mill. Shukla et al. (2012) utilized water cascade analysis technique (WCA) (Manan et al., 2004) in order to calculate the minimum freshwater consumption of a bleaching section of an Indian paper mill. Chemical oxygen demand, total dissolved solids, and adsordable organic halides (AOX) were analysed, and the latter was found to be a critical limiting constraint. A nearest neighbour algorithm (NNA) (Prakash and Shenoy, 2005) was used to design the network and distribute the fresh water and recycled water. The results showed a reduction of 41.75 % of fresh water consumption and 70.67 % of wastewater generation.
Iswalal et al. (2012) applied a water pinch analysis technique to reduce the water consumption and wastewater discharge in a South African paper mill. The main contaminant considered was total suspended solids, and the cationic demand was a dependent contaminant. After identifying the pinch point in the system, the minimum regeneration flow rate was determined by the ultimate flow rate targeting technique with regeneration placement (Ng et al., 2008). A water network was based on the nearest neighbour algorithm (Prakash and Shenoy, 2005). The results identified a potential reduction in fresh water consumption of 60 to 70 % for two paper machine of making process.
Chew et al. (2011) presented an optimization model considering simultaneously water and energy saving in a BSWS (Brown Stock Washing System) in the pulp and paper mills. The adopted model was non-linear programming (NLP), where the objective function was the total cost minimization. According to the authors, the synthesized water network resulted in a significant reduction of 17 % and 23 % of energy and water consumptions, respectively, as compared to the base case.
Chew et al. (2013), considering the same base case presented in Chew et al. (2011), proposed a new optimization model considering simultaneously the water and energy saving in the BSWS of the pulp and paper mills. They used two different models: NLP for the first scenario and a mixed integer non-linear programming (MINLP) for the second one. In the first scenario the objective function was set to minimize the total operating cost, while in the second one, the objective function was set to minimize the total annualized cost with piping consideration. According to the authors, the synthesized water network for the first scenario achieved water and energy reductions of 22 % and 24 %, respectively, and in the second scenario reductions of 21 % and 23 %, respectively, when compared to the base case model. They also carried out a sensitivity analysis to assess the relationship between washing efficiency and total operating cost reduction. It’s worth to mention that all available design methods are aimed to find only one optimum heat-integrated water using network and neglect other attractive candidates.
Moshkelani et al. (2013) presented the concept of green forest biorefinery integrated in a Kraft mill and the strategy for its progressive implementation composed of three different features: (i) Equipment Performance Analysis (EPA), (ii) System Performance Analysis (SPA), and (iii) System Interaction Analysis (SIA). The authors realized that the energy efficiency of a Kraft process is closely related to the proper management of water and steam, which must take into account their strong interactions. They implemented this methodology in a base case and concluded that the use of an intense energy optimization approach for the reference mill saves 21-34 % of the total steam consumption and 27 % of the mill fresh water consumption.
Several procedures have been developed for water resources management. Among the proposed methodologies, highlights the algorithmic-heuristic strategy Water Sources Diagram (WSD) (Gomes et al., 2013), that is a procedure which can be used in Water Allocation Problems (WAPs) aiming the synthesis of a water system with the objective of minimal external water consumption and minimal wastewater generation.

2. Water Sources Diagram (WSD) Method

WSD is a method used in industrial water management. This tool was developed to meet the criteria of simplicity, efficiency, economy and industrial applicability. In other words, is a robust technique in its scope and with a simple strategy, which can be applied in single contaminant problems (Gomes et al., 2007) and also in multiple contaminant processes (Gomes et al., 2013).
In this methodology, each operation is considered as a mass transfer device where occurs a reduction of contaminant loads with the use of water as extracting agent. The WSD divides the process in concentration intervals and water is allowed to be reused between these intervals. Concentration limits of each interval are considered internal water sources. The water supply and regenerated water are considered external water sources. These concentrations are ordered and represented into a grid of

concentrations. Then the mass load transferred ($\Delta m_{k,i}$) in each operation (k) in each interval of concentration (i) is calculated and indicated between parenthesis. To apply the WSD algorithm some heuristic rules have to be used and the main objective is to attend the mass transfer in each concentration interval, using the lower amount of external water (0 ppm). A full description of the procedure is showed by Gomes et al. (2007) for a single contaminant and by Gomes et al. (2013) for multiple contaminants, where several types of constraints are treated individually. To ensure the minimal water consumption, three rules must be followed (Gomes et al., 2007):

Rule 1: Use external water sources only when internal water sources are not available;

Rule 2: Transfer all the possible amount of contaminant inside a concentration interval;

Rule 3: For operations those are present in more than one interval, when changing interval, the stream must continue to flow through the same operation until its end (this heuristic avoids the division of operations).

For problems involving multiple contaminants, the single contaminant algorithm has been extended as can be seen in Gomes et al. (2013). The advantage of this procedure is that the network structure is obtained simultaneously with the minimum fresh water consumption target.

3. Application of the Water Sources Diagram Method – Pulp and Paper Industry

The WSD method is here applied in an example taken from Shukla et al. (2012). It involves the minimization of water consumption through maximum reuse in a bleaching section of a pulp and paper industry. The bleaching section is composed by three washers: Chlorine washer, Alkali washer and Hypo washer. According to the authors the bleaching section requires 8,628 m^3/d of fresh water and generates 5,097 m^3/d of wastewater without integration. Three contaminants is selected as significant pollution parameters in the streams: TDS (Total Dissolved Solids), COD (Chemical Oxygen Demand), and AOX (Adsordable Organic Halides). The problem data can be seen on Table 1.

Table 1: Opportunities Table (Shukla et al., 2012)

Contaminant	Flowrate Inlet (t/d)	Conc. inlet (ppm)	Operation	Contaminant	Flowrate outlet (t/d)	Conc. outlet (ppm)
COD TDS AOX	4,910	983 2,800 33.3	Chlorine Washer	COD TDS AOX	3,702	1,190 3,600 83.71
COD TDS AOX	1,930	1,120 3,900 17.59	Alkali washer	COD TDS AOX	747	2,976 7,900 34.32
COD TDS AOX	1,788	1,078 5,000 37.62	Hypo washer	COD TDS AOX	648	2,176 12,000 98.3

For WSD application, operations which present water gain or loss are divided in two parts. The first is the one with fixed flow rate and the second represents the water gain or loss. For example, Chlorine Washer (1.2), Alkali Washer (2.2) and Hypo Washer (3.2) represent water losses according to Table 2. In this process, all the washers are operations with fixed flow rates. Table 2 also shows the results for the mass transferred ($\Delta m_{k,i}$) of each contaminant in each operation, assuming the operational conditions.

With these data the WSD algorithm can be applied following the extended methodology for multiple contaminants (Gomes et al., (2013)). It is necessary the identification of a reference contaminant on which the mass transfer of all other contaminants is described, adopting a linear mass transfer relationship. In this present case study AOX is chosen as the reference contaminant. The reason is because AOX is the one which presents the lowest maximum inlet concentration in more process operations and its outlet concentrations increase monotonically along the operations. Figure 1 presents the obtained WSD considering maximum reuse.

Table 2: Limiting data of bleaching section to apply WSD

Number	Operation	Flow rate (t/d)	Contaminant	Conc. Inlet (ppm)	Conc. Outlet (ppm)	Mass load $\Delta m_{k,j}$(t/d)
1.1	Chlorine Washer	3,702	COD	983	1,190	0.77
			TDS	2,800	3,600	2.96
			AOX	33.3	83.71	0.19
1.2	Chlorine Washer	1,208	COD	983	-	1.19
			TDS	2,800	-	3.38
			AOX	33.3	-	0.04
2.1	Alkali washer	747	COD	1,120	2,976	1.39
			TDS	3,900	7,900	2.99
			AOX	17.59	34.32	0.01
2.2	Alkali washer	1,183	COD	1,120	-	1.32
			TDS	3,900	-	4.61
			AOX	17.59	-	0.02
3.1	Hypo Washer	648	COD	1,078	2,176	0.71
			TDS	5,000	12,000	4.54
			AOX	37.62	98.3	0.04
3.2	Hypo Washer	1,140	COD	1,078	-	1.23
			TDS	5,000	-	5.70
			AOX	37.62	-	0.04

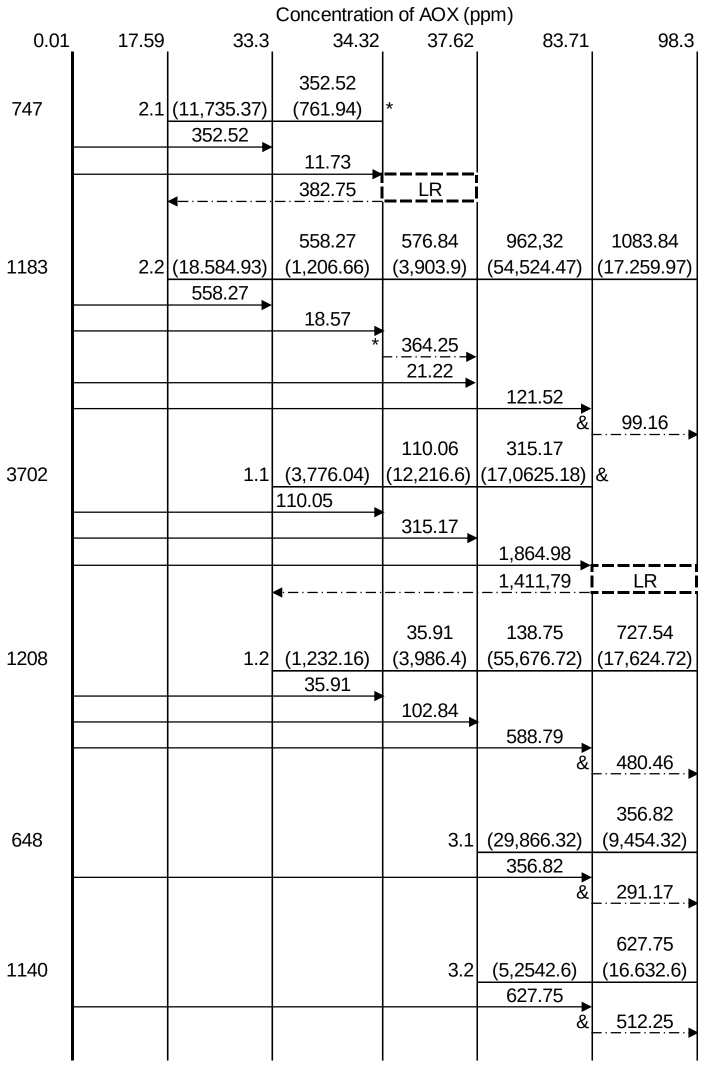

Figure 1: Final WSD adopting maximum reuse for the Case Study

It can be seen in the WSD the presence of two local recycles (LR). They were necessary to achieve the fixed flowrate constraint. The water consumption and wastewater generated obtained with the WSD are 5,086.16 t/d and 1,445.10 t/d, respectively. A pinch is located at the 83.71 ppm concentration interval (located by the higher concentration of the last interval where external water is used in the WSD). However, it is necessary to perform the mass balance to see if there is violation of concentration. Two things are worth mentioning: 1) In Chlorine washer the concentration of AOX is less than the limit, allowing a reduction in fresh water consumption; 2) There is a violation, which must be removed, of concentration in the Alkali Washer for COD contaminant. The final water consumption, after removing the violation in Alkali Washer and reducing the fresh water consumption in Chlorine Washer, is 5,085.51 t/d. This value is higher than the 5,025.56 t/d found by Shukla et al. (2012), using the Water Cascade Analysis. However, the authors did not pay attention in the concentration violation in COD from Alkali Washer, thereby achieving a non-realistic result. The water network with the final result obtained by the WSD is presented in Figure 2. The pinch point obtained in this work and in the work of Shukla et al. (2012) is the same.

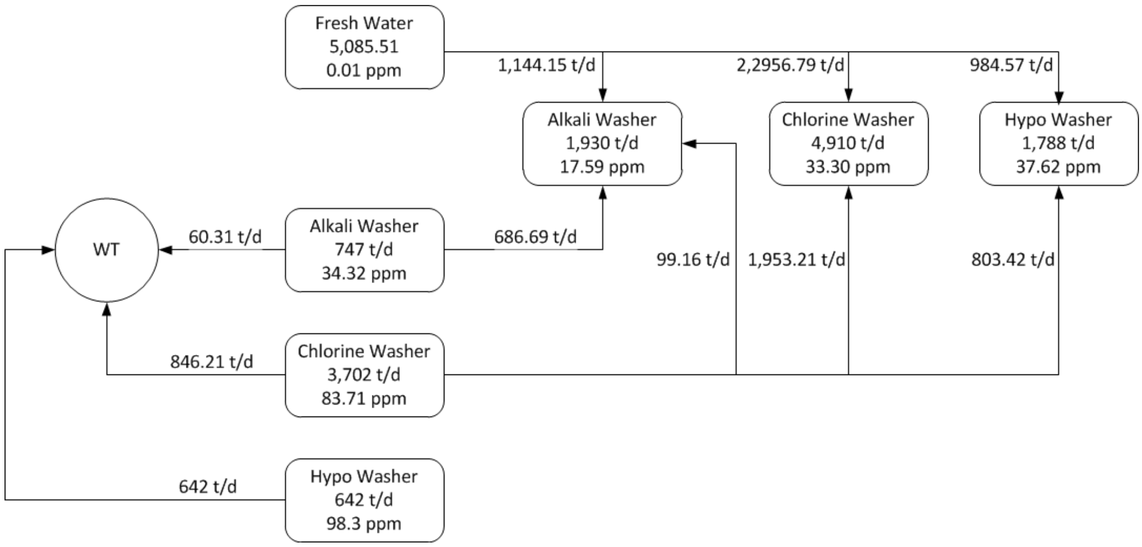

Figure 2: Final water network for bleach system obtained by WSD

With the removal of violation in the Alkali Washer, the water consumption and the wastewater generation increases and consequently changes the water network. The water network obtained in this work is similar with the Shukla et al. (2012) and the only difference is that the Alkali Washer now generates wastewater and has an increase on water consumption. Shukla et al. (2012) had to use two different methods to obtain the final result, Water Cascade Analysis for target and Nearest Neighbour Algorithm for the water network. Using the WSD, it is necessary just one tool since the water consumption and the synthesis of water network were attained simultaneously.

It was found that the total fresh water requirement is 5,085.51 t/d and the total wastewater generation is 1,548.52 t/d. The three streams of wastewater generated are: 846.21 t/d in the chlorine washer; 642 t/d in the hypo stage washer and 60.31 t/d in the alkali washer. Before applying process integration, the bleaching section requires a fresh water flow rate of 8,628 t/d and generates 5,097 t/d of wastewater; thus, after the application of WSD it is possible to reduce in 41.05 % and in 69.61 % the fresh water consumption and the wastewater generation, respectively.

4. Conclusions

This work has presented a general survey of how the management of water systems in pulp paper industries has been studied in the recent literature, identifying mathematical programming methods and algorithmic methods.

The algorithmic method WSD was applied in analysing a representative example of a bleaching section presented by Shukla et al. (2012), creating a scenario involving the possibilities for reuse, among the various alternatives that allows the procedure. The WSD indicates a possibility of a reduction of 41.05 % in the capture of raw water (external) and a reduction of 69.61 % in the wastewater discharge. The WSD has shown to be an important tool when it’s desired to set new alternatives for water reuse in a systematic and efficient manner. Its adoption is ease even in multiple contaminants processes in the context of programs of water resource management in the industry. It's was found an result reported by Shukla et al. (2012), which presents a violation in COD contaminant concentration in the alkali washer, which implies in a lower water consumption result.

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