TECHNICAL-SCIENTIFIC OPINION ATECEL/UFCG

TITLE: Evaluation of the safety of the production process, wastewater treatment and water management, certifying Alunorte's ability to operate at different levels of production, considering the possibility of extreme rainfall.

REQUESTED BY: Norsk Hydro Brasil Ltda.

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GOAL: To present the results of the evaluation of storage, pumping, and wastewater treatment systems, regarding the company's ability to operate at different levels of production (considering the years 2017 and 2018), taking into account the possibility of extreme rain and the outflow generated by the refinery.

INDEX

List of tables

List of figures

1. EXPERT ENTITY

Associação Técnico Científica Ernesto Luiz de Oliveira Júnior (ATECEL®) is a non-profit entity under private law, founded by professors of the Escola Politécnica of the Universidade Federal da Paraíba on August 05, 1967, and whose name is an homage to Professor Ernesto Luiz de Oliveira Júnior.
The basic purpose of ATECEL® is to support and facilitate research and extension programs for universities and research institutes. However, it also provides consulting services, development of projects and training in different areas of knowledge, the interaction of which is made possible through agreements or contract. The processes put in place provide the opportunity for the various sectors of the University to develop research programs and to provide services, enabling the University to fulfill its role within society.

ATECEL® develops projects (calculation and monitoring), staff training and research in the following areas: Chemical Engineering, Electrical Engineering, Civil Engineering, Mechanical Engineering, Mining and geology, Computing Systems and Materials Engineering, among others. The work in these areas has resulted in the remarkable experience of ATECEL® in carrying out projects with outstanding entities in Brazil, such as: Petrobras, CSN, Suzano Celulose, Votorantim Metais, Braskem, Alcoa, Chesf, Eletrobrás, Aperam, Vallourec & Sumitomo, Clariant, General Motors, ANEEL, ANA, CNI and FINEP. The performance of ATECEL® in the implementation of projects in these areas is the result of the great diversity of expertise of UFCG professors, which by law are allowed to work in conjunction with ATECEL®.

Law n. 8958, issued on December 20, 1994 establishes the framework for the relations between federal institutions of higher education and of scientific and technological research and support foundations. ATECEL® had the revalidation of its status as a support entity to Universidade Federal de Campina Grande (UFCG) on February 12, 2007, at a meeting of the University Council Collegiate.

Since 2014, ATECEL® implements programs for energy efficiency (EE) in Brazil, through simulation and optimization of processes and their auxiliary systems.

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2. EXECUTIVE SUMMARY

As part of the service agreement 4600006981 signed with ATECEL® in September 2018 and valid for 18 months, this report presents the results obtained in the evaluation of Alunorte's storage, pumping and wastewater treatment systems, located in Barcarena-PA.

At first, the team at ATECEL®, consisting of 14 people, including academics and market professionals, and coordinated by Professors Dr. Romildo Pereira Brito and Dr. Gilmar Trindade de Araújo, both of the UFCG, gathered for the first time with engineers from Alunorte, in order to understand the details of the event occurred between the evening of February 16 and the morning of 17, 2018.

From the above-mentioned meeting, the phase of gathering information and technical data on the system at the time of the event, and as it will be in December 2018 and in May 2019, began. Data were obtained on storage, pumping and processing capacities between basins and *sumps*; as well as information about the maneuvers between these.

The next step was the development of process flowcharts (PFDs) for February and December 2018, and May 2019; periods with different settings (including connections) of storage, pumping and/or wastewater treatment. The PFDs were validated by a team of engineers from Alunorte and then implemented in the software Aspen™ (Plus and Dynamics).

For the Aspen™ implementation, it was necessary to calculate the refinery outflow and the flow caused by rainfall.

In parallel, the work included several visits to the refinery areas, industrial wastewater treatment stations (ETEI) and deposits of solid residues (DRS), when photographic records were obtained, which are presented throughout the report.

The model implemented in Aspen™ can reproduce with satisfactory precision, from a scientific point of view, the events on February 16 and 17, 2018, in order to answer questions based on different scenarios of storage, pumping and wastewater treatment capacities, as well as levels of alumina production and rainfall.

Between 10:00 pm on 02/16/2018 and 6:00 am on 02/17/2018, after intense rainfall, excess rainwater at Alunorte's plant was released through an old channel. The decision to use the old channel to drain the excess of rain, in the assessment of the experts, was the most appropriate under the circumstances.

The results of the computer simulations show that the basins and DRS2 DRS1 did not overflow in February 2018.

Shortly after the events, in compliance with the determinations of the relevant authorities, Alunorte started to operate with an output level of 50% of its production capacity. However, the results of the simulations show that the reduction in the level of Alunorte's production of the alumina does not represent an increase in operational safety, since the processing capacity of the ETEI is significantly larger than the outflow generated by the refinery, which has low sensitivity to variation in the level of production.

In February 2018, the outflow generated by the refinery (2,100 m^3/h as calculation methodology used in this work) demanded approximately 20% of the capacity of the ETEI (9,500 m^3/h), the rest being destined to the processing of wastewater generated by rainfall.

With the new storage and pumping capacities, available in December 2018, there will be no need to use the old channel to drain excess rainwater, considering rainfall similar to that which occurred on February 16 and 17, 2018, as well as for rains with return periods equal to 10,000 and 5,000 years, with duration of 12 and 24 hours, respectively.

Upon completion of the installation of the new ETEI unit, in May 2019, there will be an increase of approximately 50% in wastewater processing capacity, which will go from 9,500 m^3/h to 14,000 m^3/h. When the new capacity is considered, the outflow generated by the refinery will represent 15% of the maximum capacity of the ETEI.

The results of the simulations indicate, precisely, that the improvement projects in the three fronts mentioned (storage, pumping and treatment), are suitable and ensure the safety of Alunorte operations. Specifically, the improvements were tested for rain with return periods equal to 10,000 and 5,000 years, with duration of 12 and 24 hours, respectively; and the results obtained from simulations show that it is not necessary to use the old channel to release rainwater.

The improvements implemented or being implemented in Alunorte meets NBR 13028 of 2017, which states that the overflow systems of geotechnical structures with high Potential Damage must be set for a return period of 1,000 years or more, during the operational period of the structure; and 10,000 years or above for the period of structure closure.

Operational procedures (maneuvers of valves and dampers) must be clear and simple, with frequent training, to ensure that in times of emergency, the system is operating as expected.

On the basis of the information obtained with Alunorte and on the results of the computer simulations, the experts affirm that the improvement projects currently running in the areas of wastewater treatment, storage and pumping are correctly sized to withstand extreme rainfall events, without the need to use the old channel to drain excess rainwater, as long as the operational procedures are followed by Alunorte.

The reviewers conclude that, currently, from the point of view of wastewater management, it is safe for Alunorte to produce at nominal fee of 6.3 million metric tons of alumina a year. With the improvement projects that are being implemented, Alunorte is prepared for possible future changes in climate, which could lead to more frequent extreme rain events, as of December 2018.

3. INTRODUCTION

Alunorte is the alumina refinery with the world's largest production capacity and is located in the State of Pará in the northern region, more specifically in the industrial district of the city of Barcarena, as shown in Figure 1. Conceived in 1978, from an agreement between the Governments of Brazil and Japan, and with the participation of the Companhia Vale do Rio Doce (CVRD), it was created as a way to ensure the production cycle of aluminum in the state, beginning its operations in 1995 with 450 professionals.

Figure 1 - Alunorte's Industrial Unit.

Since the beginning of its production, the company went through three cycles of expansions, completed in 2003, 2006 and 2008, making possible the elevation of its nominal production capacity of 1.1 Mt/year to 6.3 Mt/yr of alumina, generating approximately 8,000 direct and indirect jobs, having, in its majority, employees from Pará (Alunorte, 2018a).

In financial terms, the first expansion required an investment of US$264 million, allowing an increase in production to 2.5 Mt/yr of alumina. As a result, the second expansion, completed in 2006, stood out by putting the Alunorte in the leading position in world production of alumina due to an investment of US$768 million, increasing the production capacity to 4.4 Mt/year. The last expansion, approved in 2005, resulted in the largest investment made so far, with the value of US$846 million, and secured an increase in productive capacity to the current level of 6.3 Mt/year (Alunorte 2018b).

In 2011, the Group of the Norwegian company Norsk Hydro bought the shares from Vale and three other companies linked to the chain of aluminum production in Pará (Mineração Paragominas, Albrás and CAP), in a vertical production process of integrated assets, operating from the bauxite mining to the production of aluminum finished products. Thus, Norsk Hydro established position in three strategically important world regions, rich in mineral resources: Brazil, Northern Europe and Qatar. Norsk Hydro is a multinational company present in 40 countries, operating for 85 years in the production of aluminum and electricity.

Alunorte's refinery is situated in a complex that involves the whole chain of aluminum production, including Paragominas, where the extraction of bauxite takes place, the refinery where there is the transformation of the bauxite into alumina and Albrás, the unit that receives part of Alunorte's alumina production and uses it for the production of around 460,000 tonnes of aluminum, being the second largest aluminum producer in Brazil.

Aluminum is the third main product of the trade balance of Pará and represents 6.7 percent of the State's exports, behind only iron ore (57%) and copper ore (14%). Currently, Alunorte is the 27th largest exporter in the country, a position it occupies after the Court order issued on 03/01/2018, which ordered the cut in the level of production to 50% of the company's capacity – formerly, Alunorte occupied the 14th position.

According to a survey conducted by IBGE for 2017, Alunorte accounted for 63.5% of the gross domestic product of the municipality of Barcarena-PA. When one considers the production of aluminum and the service sector, the aluminum chain reaches 89% the GDP of the city, where 50% of the collection of taxes by the city of Barcarena comes from refinery activities.

Alunorte has become national news in recent months, after intense rain events occurred on February 16 and 17, 2018 in the region of Barcarena, when flooding was observed in the region and at Alunorte's plant. During the events, the water treatment system of the plant, which receives both wastewater from the refinery process and water from the rainwater storage basins, operated in its maximum capacity. Due to the chance of leakage, local contamination and release of non-treated wastewater into the Pará River, a series of inspections at Alunorte was carried out by the competent authorities.

On February 28, 2018, the Barcarena court ordered, at the request of the Prosecution Office: (a) prohibition on using the DSR2 until the Operations License is granted, the effective operational capacity and structural safety are proved, the slopes reassessed, and all the other construction technical requirements, cumulatively; (b) plant production reduction to a level equivalent to 50% of the average monthly production of the last twelve months or to the lowest monthly production level in the past ten years, whichever is the lowest; (c) fine in the amount of R$ 1,000,000.00 (one million Brazilian reais), per day, if the orders are not complied with.

This technical report presents the results obtained from a technical, objective assessment regarding the rainwater and waste water storage systems, and their pumping system (including maneuverability), the processing capacity of the Industrial Wastewater Treatment Plants (ETEIs), as well as an assessment of the volume of wastewater generated for different levels of alumina refinery production.

For the implementation of the technical evaluation about the topics mentioned, the team at ATECEL®, represented by a group composed of 14 academics from UFCG and market professionals, all linked to the Alliance of Industrial Competitiveness Program of the National Confederation of industry (CNI), conducted a series of technical evaluations at Alunorte's refinery throughout the month of October 2018, among which stand out:

- Analysis on the engineering calculations and studies carried out by teams from Alunorte and its contractors on the rain events that occurred in the month of February 2018, emergency actions taken, the standard procedures for operation of the refinery in days of intense rain, and includes evaluation regarding the laboratory tests of the quality parameters of the wastewater released and mass balances.
- Field inspections in the areas of the refinery, including all rainwater and wastewater storage basins, intermediate tanks (called "*sumps*"), drainage and pumping system, adjacent and peripheral areas of the refinery, in addition to the main production systems of alumina, such as digestion, clarification, precipitation, evaporation and calcination.
- Evaluation of the improvement projects in the storage areas of water and wastewater, as well as the project of increasing the capacity of processing and treatment of ETEI.
- Application of the most modern techniques of computer modeling and simulation for dynamic verification of the behavior of all the storage basins, *sumps,* the capacity and bottlenecks of wastewater transfer between the basins on different levels of rain (considering average volume and located downpour) and different levels of alumina production with subsequent industrial wastewater generation, by implementing the Aspen™ software, the computational tool most appropriate and used for chemical industrial processes.
- Photographic record of all points of improvement and increase of capacity of water and wastewater storage of water, as well as the peripheral regions of the plant, and the wastewater outfall in the Pará River and ETEI.

- Classification of all documents, presentations, technical drawings, calculations and spreadsheets used by Alunorte as evidence of actions taken because of the rainfall events, and which were used in the observations and conclusions made by ATECEL®.

4. CONTEXT - THE EVENT THAT TOOK PLACE ON FEBRUARY 16 AND 17, 2018

During the days of February 16 and 17, 2018, the region of the city of Barcarena, where Alunorte's refinery is located, was hit by heavy rains, registering a rainfall of more than 230 mm in a 12-hour period, as recorded at Alunorte's rainfall station and shown in Figure 2.

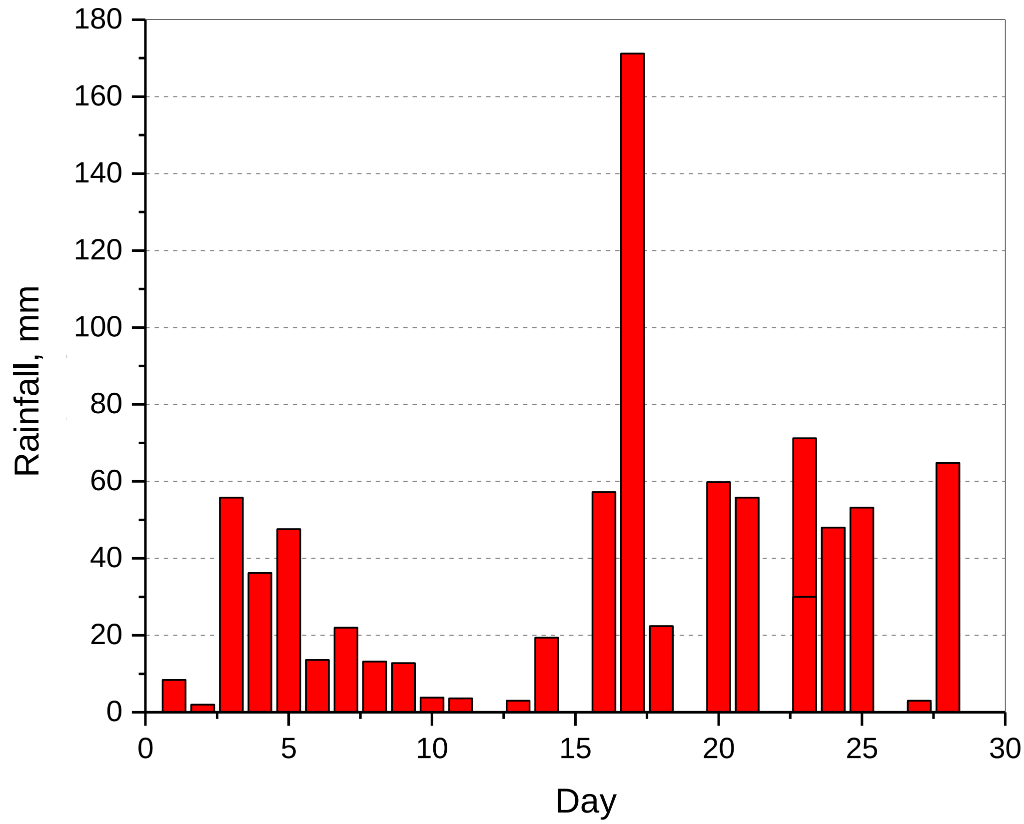


Figure 2 - Rainfall at the refinery in February 2018, according to Alunorte's rainfall station records.

As a result of that volume of rain, floods were recorded in some parts of the city of Barcarena-PA and within the area of Alunorte's industrial unit, as shown in Figure 3, and as has been widely reported by channels of communication and media of the State of Pará and Brazil.

Inside Alunorte some flooding was registered, in particular, in the area called the A45, where there is a rainwater collector, associated with a set of bombs (*sump* 45) and in the emergency basin, in the area of ETEI.

In the DRS2 area, the operation in situations of extreme rainfall, such as those presented above, occurred as planned, i.e. rainwater was directed, through overflow systems, from the inner region of the deposit to the channel called "keyway". Behind the keyway, there are two other channels, the first called adduction channel and the second, sedimentation channel, and both are responsible for receiving the volume of water from inside the Deposit (whose single goal is to store bauxite solid waste) and direct this wastewater to the storage basins.

(a)

(b)

(c)

Figure 3 - *Picture of the area of the* sump 45 which shows the accumulation of rainwater inside Alunorte:) on 02/17/2018; b) on 10/31/2018; c) location in the area of the refinery.

Figure 4 shows the areas that receive bauxite solid residue (A), the channel called keyway (B), (C) sedimentation channel and the outline or adduction channel (D).

The DRS2 project was designed so that all rainwater received by the area of solid waste (A), be transported to the underlying channels and directed to the storage basins and further processing in the ETEIs. As the only objective of the DRS2 area is to store bauxite solid waste, the rainwater initially accumulates on the waste and, by gravity, flows through overflow systems (E), which are small transverse channels between the slopes, as shown in Figure 5.

Figure 5 shows that there has been wastewater overflow at the lowest spot, called overflow pipe, which is provided for in the project exactly for these situations. What the technical staff of Atecel/UFCG found through documentary analysis, photographic records, field inspections conducted within and outside Alunorte, was an increase in the level of liquid inside the DRS2 depending on the volume of rain in the period mentioned.

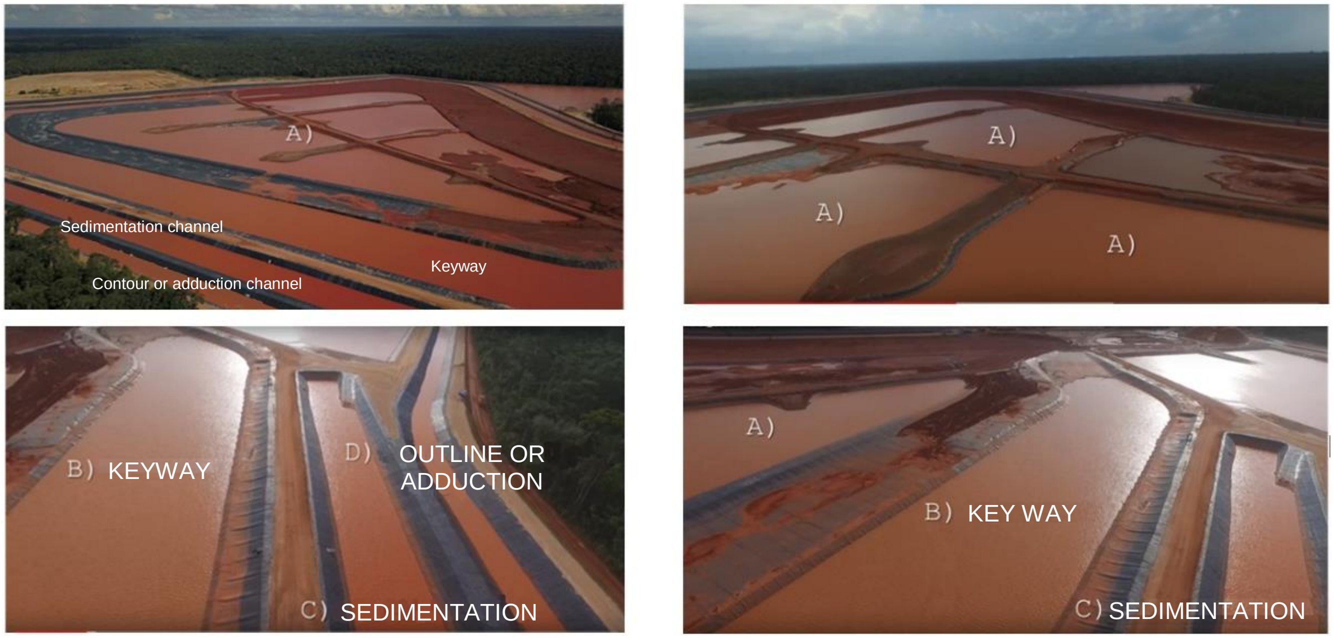


Figure 4 - Details of DRS2.

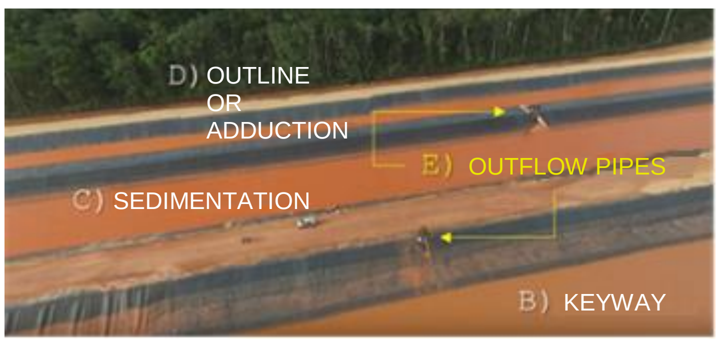


Figure 5 - DRS2 details showing overflow between channels.

It is important to note that photographic records should always be taken into account with care, as they can lead to erroneous conclusions when assessed in isolation. Depending on the use of a photographic record, without an equivalent technical and scientific reasoning, incorrect information can cause significant inconvenience to society in general, because emergency measures can be triggered leading to decisions on the part of the population, public authorities, regulatory agencies and private institutions that can potentially bring harm to the common good, even if the intention of an alert is the concern with the well-being and safety of society.

During the rain events, started on February 16, the operation of Alunorte was maintained as usual, as per operational procedures. The operation of the refinery is designed to process and treat both wastewater from the production process (called Bayer alumina production Process), and to store and treat rainwater that constantly falls on the areas belonging to Alunorte.

At or around 11:40 pm of February 16, 2018, the increase in the rain intensity was registered in the operation and management system of the refinery, by operators who were working at that moment, and, shortly thereafter, an electrical discharge in the area of the refinery that affected some ETEI equipments, pumping systems and some engines in *sumps* was also registered. It was found, through document records, that these circumstances led to an increase in the storage basin level, since the wastewater and rainwater transport to the treatment plant had been harmed (according to documentation made available to the competent authorities, according to Alunorte).

The energy of the plant was reestablished at 12:30 am, and during this interval, the ETEIs continued to operate partially.

When the levels of the storage basins, excluding DRS1 and DRS2 basins, had reached 100% capacity, the old channel was used to release the excess water. All rainwater, that is, without contamination, was segregated to avoid a possible overload in the ETEIs which could cause release of wastewater out of specification. Figure 6 shows the location of the old and new channels in the area of the refinery.

Figure 6 - "Old" and "New" Channels.

On February 17 and 18, the competent authorities conducted inspections at Alunorte, with the technical support of the plant’s experts. On this occasion, it was also verified the existence of a small rainwater leak in an old pipe located next to a warehouse area, an area of the refinery without industrial operations and that drains the *sump* 45, which was immediately buffered (Figure 7).

Figure 7 - External Pipe to sump 45 area.

On February 22, Instituto Evandro Chagas reported measurements of samples in the immediate vicinity of the plant. Due to these events and the doubts about the possible impacts, the Court of the District of Barcarena, on February 28, 2018, ordered the 50% reduction of the company's production of alumina.

From then on, Alunorte started a series of measures aimed at meeting the most urgent needs of the plant and of the communities located in the immediate vicinity of the plant. Some of the improvements that have been implemented are listed below.

- Establishment of a task force of internal experts for comprehensive review and analysis of available data, in order to propose actions for possible improvements;
- Collection of samples to determine the quality of the water;
- Improvements to some drainage points;
- The company undertook to act in conjunction with social partners to invest in the supply of drinking water to the neighboring communities of Alunorte.

In addition to actions already performed, Alunorte keeps on implementing medium-and long-term initiatives aimed at the modernization and improvement of the plant, some of which are presented below.

- Improvements to the water management systems and treatment capacity, maintenance of systems and of the emergency plans and training;
- Implementation of a new system of floodgates;
- Investment of around R$200 million in the refinery's water treatment system, increasing treatment capacity at 4,500 m^3/h, 242,930m^3 in storage, and 17,000 m^3/h in pumping;
- Update of the emergency procedures, including the review of the practices of communication with local communities during and after emergencies, as well as training to the neighboring communities of Alunorte;

- Maintenance and modernization of equipment, including opportunities for improvement identified in reports issued by hired consultants;
- Review on the collecting, testing, analysis and monitoring of environmental and health data process, including water quality;
- Creation of the project Sustainable Barcarena, offering R$100 million for actions that provide training, establishing a public platform for monitoring and data assessment, and development of social and environmental projects.

It is worth noting that in the midst of these initiatives, Alunorte signed on September 05, 2018, 2 agreements toward the resumption of normal operations in the alumina refinery. However, with the ban on the use of the filter press and DRS2, on October 3 it was announced the total suspension of the plant's operation, after the verification that there were risks in the operation of the DRS1 with drum filter waste, due to its volume of solids. Then, IBAMA authorized, exceptionally, Alunorte to use its filter press technology in the processing of bauxite residue, which enabled Alunorte to continue its operations.

5. SPECIFIC OBJECTIVES

To fully comply with the general objective, the following specific objectives have been defined:

- Obtain and evaluate historic data of rainfall for the period of the event;
- Obtain and evaluate basins and *sumps* projects' data on the date of the event;
- Obtain and evaluate wastewater pumping system project data on the date of the event;
- Obtain and evaluate industrial wastewater pumping system project data on the date of the event;
- Obtain and evaluate basins and *sumps* projects' data for December 2018 and May 2019;
- Obtain and evaluate data of wastewater generation during the years 2017 and 2018;
- Obtain and evaluate the PFD (*Process Flow Diagram*) for the wastewater circuit during the event;
- Obtain and evaluate the PFD for the wastewater circuit for December 2018 and may 2019;
- Using the Aspen Plus™ Simulator, implement in stationary regime the process flow of the wastewater circuit, including the storage capacities of basins and *sumps,* the pumping system and the wastewater treatment system;
- Using the Aspen Plus™ Simulator, implement in transient regime the process flow of the wastewater circuit, including the storage capacities of basins and *sumps,* the pumping system and the wastewater treatment system;
- Generate and evaluate different scenarios of refinery operation with and without rainfall;
- Evaluate the operating procedures of the refinery and ETEI with and without rainfall.

6. SUMMARIZED DESCRIPTION OF THE ALUMINA PRODUCTION PROCESS (Al2O3)

In 1888, Karl Josef Bayer developed and patented the process internationally known today as Bayer Process. The Bayer Process is used for refining the bauxite (named so because of the first commercial mining took place in *LesBaux*, France) in the production of alumina (Habashi, 2005). The Bayer process is used to this day practically without significant changes, only with the substitution of sodium carbonate by sodium hydroxide and the use of pressure during digestion (Hind, 1999; Habashi, 2005).

The alumina production process begins in the treatment of bauxite, the main raw material in the Bayer process, as shown in the flowchart presented in Figure 8.

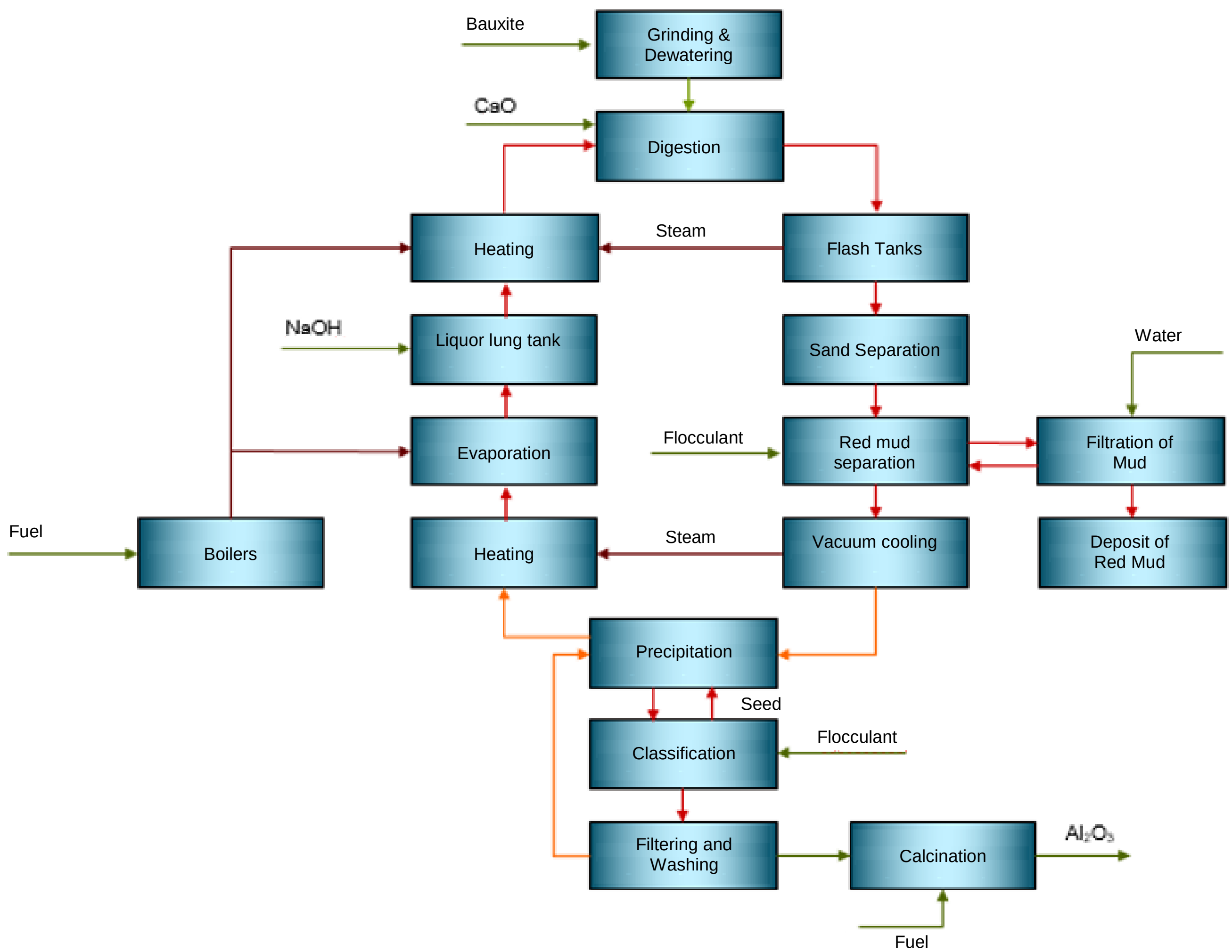


Figure 8 - Simplified Flowchart of the Bayer Process.

The bauxite is extracted, ground and homogenized wet with a solution of caustic soda, sodium aluminate and sodium carbonate. The grind has as main objective to increase the contact area of the aluminum hydroxide contained in bauxite with caustic soda to make it possible to obtain a high degree of conversion of the reaction.

The paste made from grinding heads for the stage of digestion in autoclave type reactors, under high pressure and temperature, in a solution with high concentration of caustic soda, so the following reaction occurs:

$$NaOH + Al(OH)_3 \leftrightarrow NaAlO_2 + 2H_2O$$

Once the stage of digestion is completed, the resulting paste is cooled in *flash* tanks by expansion at low pressure, and, in this way, the steam from these tanks is used to preheat the caustic solution that returns to the digesters. As a result, clarification occurs, where it separates the product of digestion between solid and liquid. In other words, it is the point where the sodium aluminate solution is separated from the solid residue rich in iron oxide, also known as bauxite residue. The clarification is usually composed of 4 essential steps: mud thickening, liquor filtering, mud wash and storage of mud in the solid waste deposit (Torres, 2001).

The steps of digestion and clarifying occur in a sector of production called red zone, because of the color of mud and wastewater produced. The product of the clarification, a liquor rich in aluminate, is more dilute and has lower temperature that the liquor contained in the paste in the digestion due to the addition of water to wash the mud. This same liquor is cooled in *flash* tanks by vacuum expansion, so that the heat released from the expansion (*flash*) is also used to preheat the caustic solution that goes in the direction of digestion and grinding, which sets up one more step that involves energy integration. In addition to cool the liquor, the vacuum cooling area helps in controlling the volume of wastewater of the plant through the retention of water (condensate) from the thermal exchange between the steam from the liquor, and the poor liquor (Santana, 2012).

The caustic solution rich in aluminate, and now cooled, head for the crystallizers, so that from the addition of the seeds, the precipitation of aluminum hydroxide starts. The reaction of precipitation is divided into two stages: gathering solids from the seed and the formation of precipitate between the particles of these clusters.

The main reaction that occurs in this step is shown below.

$$NaAlO_2 + 2H_2O \leftrightarrow NaOH + Al(OH)_3$$

As it can be seen, the precipitation reaction of the hydrate is the reverse of the dissolving reaction occurred in step of digestion (Santos, 2012).

From the precipitation there are two streams, a poor liquor, which is low in sodium aluminate, and a chain with a high concentration of hydrate of alumina in suspension. In this way, the clusters present in the carbohydrate chain are classified according to their granulometry in decanters tanks, where the thick material is separated as a product to be calcined, while the thin material is used as seed in crystallizers. Soon, the larger clusters are filtered from the caustic solution, rinsed and calcined.

The calcination occurs predominantly in fluidized bed furnaces where the combustion air is impelled in counter-flow against the hydrate, in order to minimize energy consumption, thus creating, alumina. Meanwhile, the caustic solution that is now low in sodium aluminate and with lower concentrations of carbonate and sodium hydroxide, passes through evaporation, whose main goal is the withdrawal of the dilution water. It is important to highlight that the evaporation step is vital to the profitability of the process, since it ensures the recovery of part of the caustic soda used in step of digestion, and is responsible for maintaining the balance between the water inlet and outlet in the process.

In a more didactic manner, Figure 9 shows the distribution of each step of the Bayer process between the red and white areas.

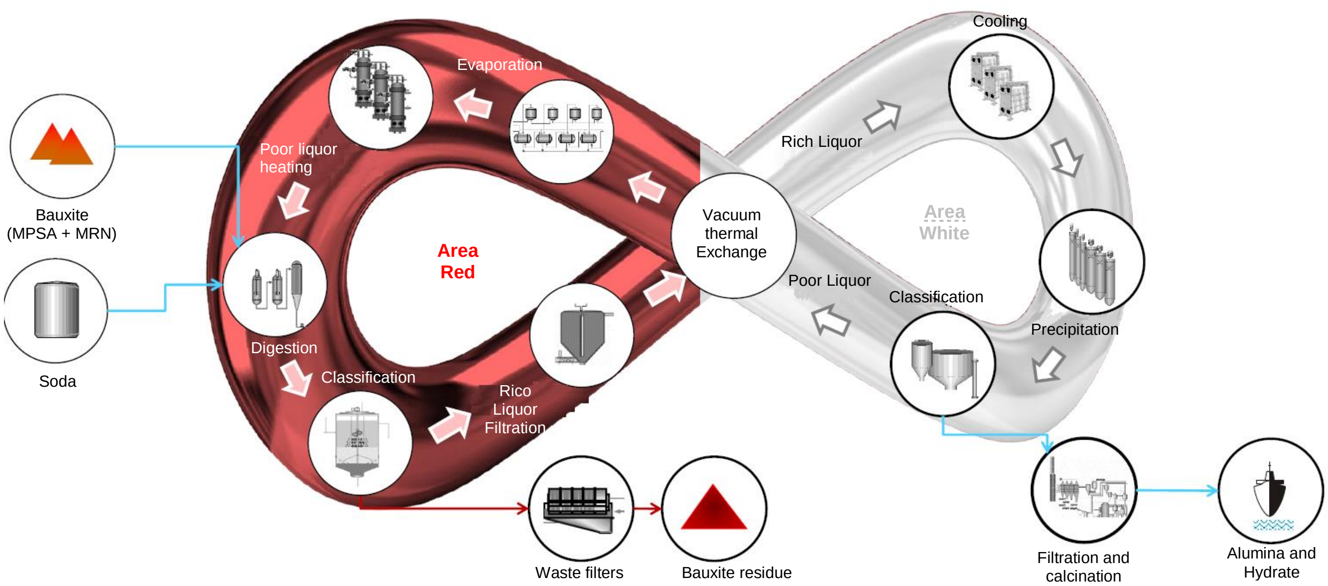


Figure 9 - Division of the Bayer process between the red and white areas.

With regard to the treatment of wastewater, including the one generated by the water used in the pipeline, the system has with neutralization tanks and clarifiers, so that the neutralization of wastewater is performed through the application of sulphuric acid and happens in three steps in tanks with mechanical agitation. The pH control is performed during all stages of neutralization, correcting the pH of about 8 to 14 to about 7.5 to 8.

After the neutralization of wastewater, the decantation of the solids is conducted through the use of flocculant in clarifiers, in order to obtain a treated wastewater (*overflow*) with the turbidity limit below the limits established by the law. The treated wastewater in clarifiers is then disposed according to the requirements of the current legislation (CONAMA Resolution n. 430, May 13, 2011), while the *underflow* (the mud from the process of clarifying the wastewater) is forwarded to the filters, and then to the deposit of solid waste.

In relation to solid wastes, Alunorte uses the method of mud disposal by high density, which consists of a process of "*dry-stacking*", patented by German company Giulini**.** In the case of DRS1, drum type filters can filter the bauxite residue to remove existing caustic soda, providing a pulp with the solids of around 65%. Meanwhile, for the DRS2, the technology adopted is that of the press filter, which allows for a much more dry residue with the solid content of 78%, which facilitates the transport of waste by means of conveyor belts. In both cases, it becomes possible to avoid segregation of liquids, so that the red mud acquire the consistency of a natural soil in short time, easing the recovery of the area for other purposes.

Figure 10 shows the difference between the pulp from the drum filter (a) and the residue after passing by press filter (b).

(a)

(b)

Figure 10 - Red mud after filtration in the drum filter (a) and (b) press filter.

By using the method *dry-stacking* for the disposal of solid waste, there are numerous advantages from the environmental point of view and of procedure, which are listed below.

- Greater recovery of the filtrate material (caustic soda), reducing environmental hazards, the operating cost and the risk of injury by contact;
- Less use of chemicals in the neutralization step;
- Safer deposit of waste, since the residue is almost dry;

- The characteristics of the residue makes it attractive for other industrial applications;
- Lower emissions of CO and CO_2 due to the reduction in the use of dump trucks.

The diagram in Figure 11 illustrates the process whereby solid wastes pass, since it uses the technology of the press filter.

Figure 11 - Steps in the treatment of solid waste.

7. PROJECT DATA, ESTIMATES AND COMPUTATIONAL IMPLEMENTATION

The methodology for carrying out the work consisted of the following steps:

- Development and validation of the PFDs;
- Project data: basins, *sumps*, pumping and ETEIs;
- Calculation of water flow generated by rainfall;
- Calculation of the outflow generated by the refinery;
- Implementation of PFDs in the process simulator Aspen™.

Process Flowcharts (PFD) and Wastewater storage, pumping, and treatment capacity

Three PFDs were developed and validated with the technical team of Alunorte: February 2018, December 2018 and May 2019. The one of February 2018 was the PFD used during the event between 16 and 17; the other two are results of project modifications. Wastewater basins, *sumps*, pumping, and processing storage capacity also has been validated by the technical staff of Alunorte.

Alunorte refinery has a drainage system consisting of 7 circuits (CC1, CC2, CC3, CC4, CC5, CC6, CC7) responsible for collecting wastewater from the industrial plant and rainwater (Figure 12). All these circuits are directed to a mixing box, where the quality of the wastewater drain circuits is monitored, in order to ensure the following parameters:

- Ph: 5 to 9;
- Temperature: < 40° C;
- Conductivity: < 3,500 µS/cm ^{2}.

In case of any change in any of these parameters, monitored continuously, by instrumentation, samples are collected in each circuit pipe and in the collection bin, in order to identify which of the drainage systems is causing a disturbance in wastewater quality. In case of contamination of any of the circuits, the floodgate directed to the mixing box is closed and the wastewater of this circuit is directed to the collection bin, and then is sent to predetermined tanks at the refinery, which are located in the area named 28 A/C.

The drainage system also has damping basins, called *sumps*. These, in their turn, have a structure with a temporary volume (*buffer*) for intense rain, avoiding flooding in their respective areas.

Figure 12 - Panoramic view of the wastewater collection system from industrial plant and rainwater.

Wastewater with caustic concentration below 2 g/L, equivalent to a pH of up to 10.5, are directed to the ETEI, where they are preferably sent to the storage basins T-82C-2A/B/C/D and T-82D-2A.

From these storage basins, liquid wastewater is sent to treatment at stations 82C and 82D. respectively. Basin T-82C-2A/B/C/D also receives wastewater from *sump* 45 and the hydrate *sump*. The emergency basin can be triggered in two ways: through the new channel where the floodgate to the basins of the expansions (C) and (D) is closed and the wastewater is directed to the emergency basin, or through a floodgate between T-82C-2A/B/C/D and the basin of emergency (T-82C-2E). In addition to the routes mentioned, the basins of the coal and bauxite areas can forward their wastewater to the T-82C-2E intermittently.

DRS1 has a channel that involves all of its extension. This channel is responsible for directing all the wastewater from the humidity of the solid waste produced in the Bayer process, in addition to rainwater, to the containment basins (Figure 13). DRS1 has two buffer basins (BC03 and BC05) and 3 control basins (BC01, BC02 and BC06), the latter contain a pumping station and are responsible for the control of the deposit basins' level. Area 54 (DRS1 and surrounding areas) also has two *sumps* (54A and 54B), which pump the wastewater collected to basins 02 and 01, respectively.

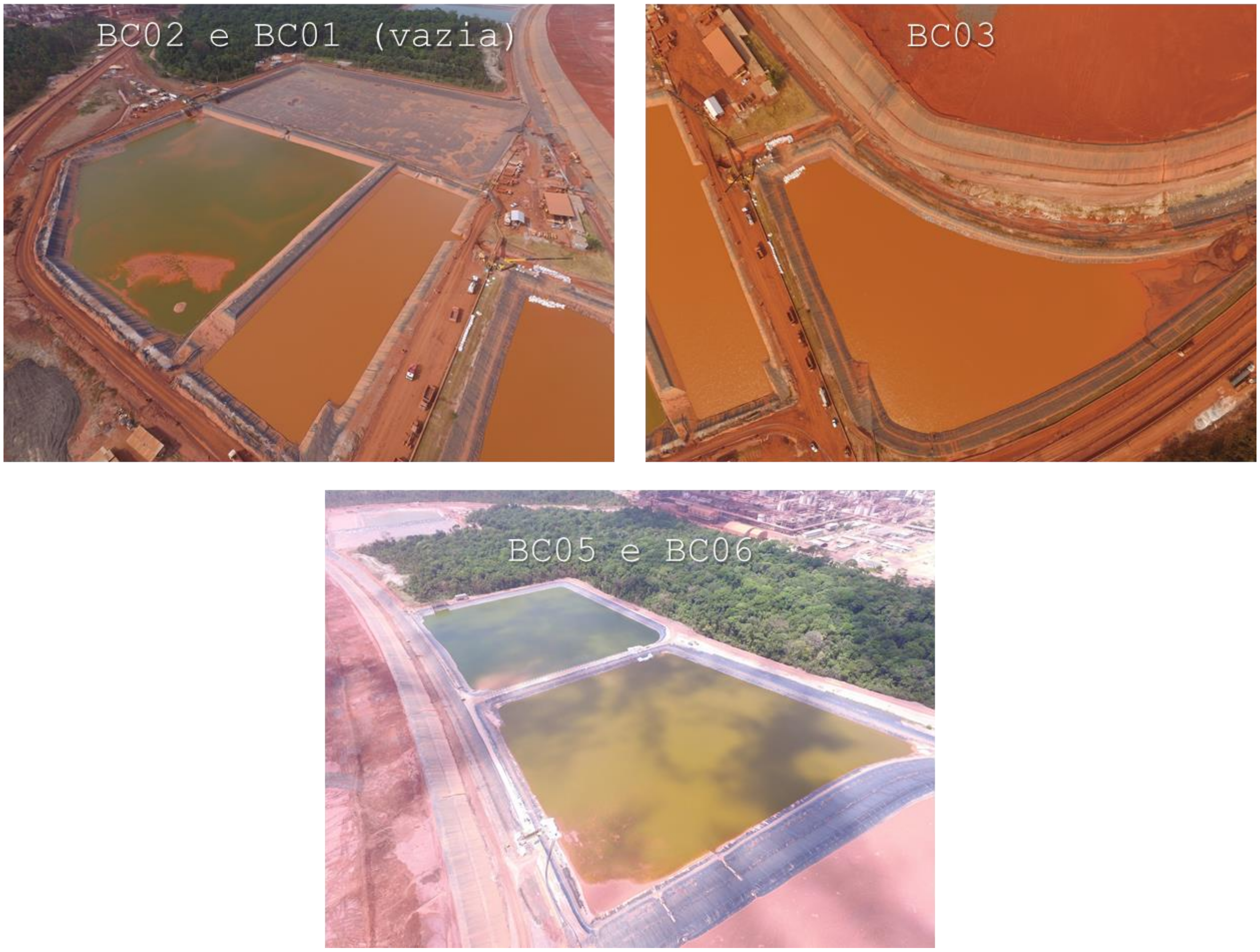


Figure 13 - DRS1 Basins.

DRS1’s contour channel flows into basins BC01 and BC03 which are connected with BC02 through a spillway and a floodgate, respectively. The same channel directs wastewater into BC05, which has a connection with BC06 through a floodgate. Control basins, in their turn, pump the waste to the area 82, where they are stored and treated before being disposed in the Pará River. Basin 02 forwards the wastewater to T-82D.-2A and Basin 01 to T-82C-2A/B/C/D. Basin 06 directs the wastewater directly to the treatment station 82E.

As well as DRS1, DRS2 has two channels that surround the area of solid waste deposit from the press filter. These channels are named as channel of sedimentation and adduction channel. The adduction channel directs the wastewater to the basins BC-201 BC-202, both having pump stations (Figure 14). Their wastewater are then united and are directed preferentially to the BC06 of DRS1. However, there are settings that allows for the transfer of the wastewater to the basins BC01 and BC02.

Figure 14 - DRS2 Basins.

Tables 1-10 present the volumes of the basins, pumping and treatment capacity, and catchment area on February 16 and 17, 2018. In the case of the volume, it was considered an average silting of 20%.

Table 1 - Volume of DRS1 basins in February 2018.

Basin	Total volume (m³)	Effective volume (m³)	Source
BC-01*	253,425	202,740	Pimenta de Ávila Report
BC-02	230,925	184,740	Pimenta de Ávila Report
BC-03	118,525	94,820	Pimenta de Ávila Report
BC-05*	471,009	376,807	Pimenta de Ávila Report
BC-06	452,147	361,718	Pimenta de Ávila Report

*Considering the volume of the North Channel (stretches 4 and 6, respectively) and the former BC-07.

Table 2 - Volume of DRS1 basins in February 2018.

Basin	Total volume (m³)	Effective volume (m³)	Source
BC-201 *	461,519	369,215	Pimenta de Ávila Report
BC-202 *	699,125	559,300	Pimenta de Ávila Report

*Considering the volume of internal and external channels.

Table 3 - Volume of ETEI basins in February 2018.

Basin	Total volume (m³)	Effective volume (m³)	Source
T-82C-2ABCD	33,295	26,636	CD394097Z001
T-82C-2E	26,711	21,368	CD394097Z001
T-82D-2AB	46,828	37,462	CD394097Z001

Table 4 - *Volume of* Sumps basins in February 2018.

Basins/Sumps	Total volume (m³)	Effective volume (m³)	Source
Sump Hydrate	9,000	7,200	Pimenta de Ávila Report
Sump-45	3,174	2,539	Pimenta de Ávila Report
Sump-54A	5,628	4,502	Pimenta de Ávila Report
Sump-54B	2.443	1,954	Pimenta de Ávila Report
Coal and bauxite areas	10,936	8,748	Pimenta de Ávila Report

Table 5 - ETEI processing capacity in February 2018.

ETEI's	Nominal Capacity	Operational Capacity	Source
ETE-82C	3,600	3,240	CD394097Z001
ETE-82D	2,800	2,520	CD394097Z001
ETE-82E	3,100	2,790	CD394097Z001

Table 6 - DRS1 catchment area in February 2018.

Basin	Catchment area (m²)	Source
BC-01	98,000 *	Pimenta de Ávila Report
BC-02	98,000 *	Pimenta de Ávila Report
BC-03	34,000	Pimenta de Ávila Report
BC-05	186,000 *	Pimenta de Ávila Report
BC-06	70,000	Pimenta de Ávila Report
DRS-1	2,957,000 **	Pimenta de Ávila Report

** Total DRS1 area, minus the area of stretches 4 and 6 of the North Channel, respectively.

* Considering the area of stretches 4 and 6 of the North Channel

Table 7 - DRS2 catchment area in February 2018.

Basin	Area (m²)	Source
BC-201	180,492	Pimenta de Ávila Report
BC-202	213,511	Pimenta de Ávila Report
DRS-2	728,000	Pimenta de Ávila Report

Table 8 - ETEI basins catchment area in February 2018.

Basin	Area (m²)	Source
T-82C-2ABCD	37,000	Pimenta de Ávila Report
T-82C-2E	19,000	Pimenta de Ávila Report
T-82D-2AB	16,000	Pimenta de Ávila Report

Table 9 - Sumps' basins catchment area in February 2018.

Basin/*Sump*	Catchment area (m²)	Source
Sump Hydrate	153,000	Pimenta de Ávila Report
SUMP-45	199,000	Pimenta de Ávila Report
SUMP-54A	95.000	Pimenta de Ávila Report
SUMP-54B	30,000	Pimenta de Ávila Report
Coal and bauxite areas	276,000	Pimenta de Ávila Report
Refinery	792,000	Pimenta de Ávila Report

Table 10 - Pumping Capacity in February 2018.

Origin	Destination	Flow (m³/hr)
BC-1	T-82C	2,100
BC-2	T-82D	2,100
BC-201/BC-202	BC-1/2/6	1,878
BC-6	82E	1,500
Line (T-82D -> 82D)	82E	600
Sump Hydrate	T-82C	350
Sump-45	T-82C	500
Sump-54A	BC-02	1,300
Sump-54B	BC-01	1,000
Coal and bauxite areas	Emergency basin	200
82C	Header	-
82F	Header	-

Figure 15 presents the aforementioned basins, while Figure 16 displays the PFD of Alunorte's wastewater circuit in February 2018.

Due to increased rainfall observed in 2018, Alunorte prepared a water resources management project, in order to increase storage and treatment capacity of industrial wastewater and rainwater, in addition to enlarging the pumping systems.

In the timeline of the wastewater circuit improvements there are two dates for delivery of the works; the shortest, December 2018, has as main objective the construction of a new basin (T-82F-2A/B/C).

This new basin will receive wastewater from T-82C-2A/B/C/D and BC02 and can redirect the wastewater again for area 82, where it will be treated. Improvements adopted in December can be observed in Figure 17.

Figure 15 - Setup of DRS1 and DRS2 basins.

In addition to the new *buffer*, which will incorporate the volume of *sump* 45 to its total volume, the work to increase the levels of the outer edges of the channel that provides access to the river and to the basins of areas 82C and 82D, has already been carried out, with the aim to further enhance the storage capacity of the basins of the area 82. To raise these levels, *Big Bag's* filled with sand are being used, as per the engineering design and with the agreement of SEMAS-PA. The basins in the coal and bauxite areas will have their volumes increased to receive rainwater. The volumes of DRS1 and DRS2 basins will remain the same, as well as those of the *sump* hydrate, *sump* 54A and *sump* 54B.

The increase of storage capacity is accompanied by an increase in the pumping systems, which allows the transfer of a greater outflow, as well as the reduction of the catchment area for the *sumps*. Tables 11, 12 and 13 feature the new storage, pumping and collection capacity for the scenarios in December 2018 and May 2019.

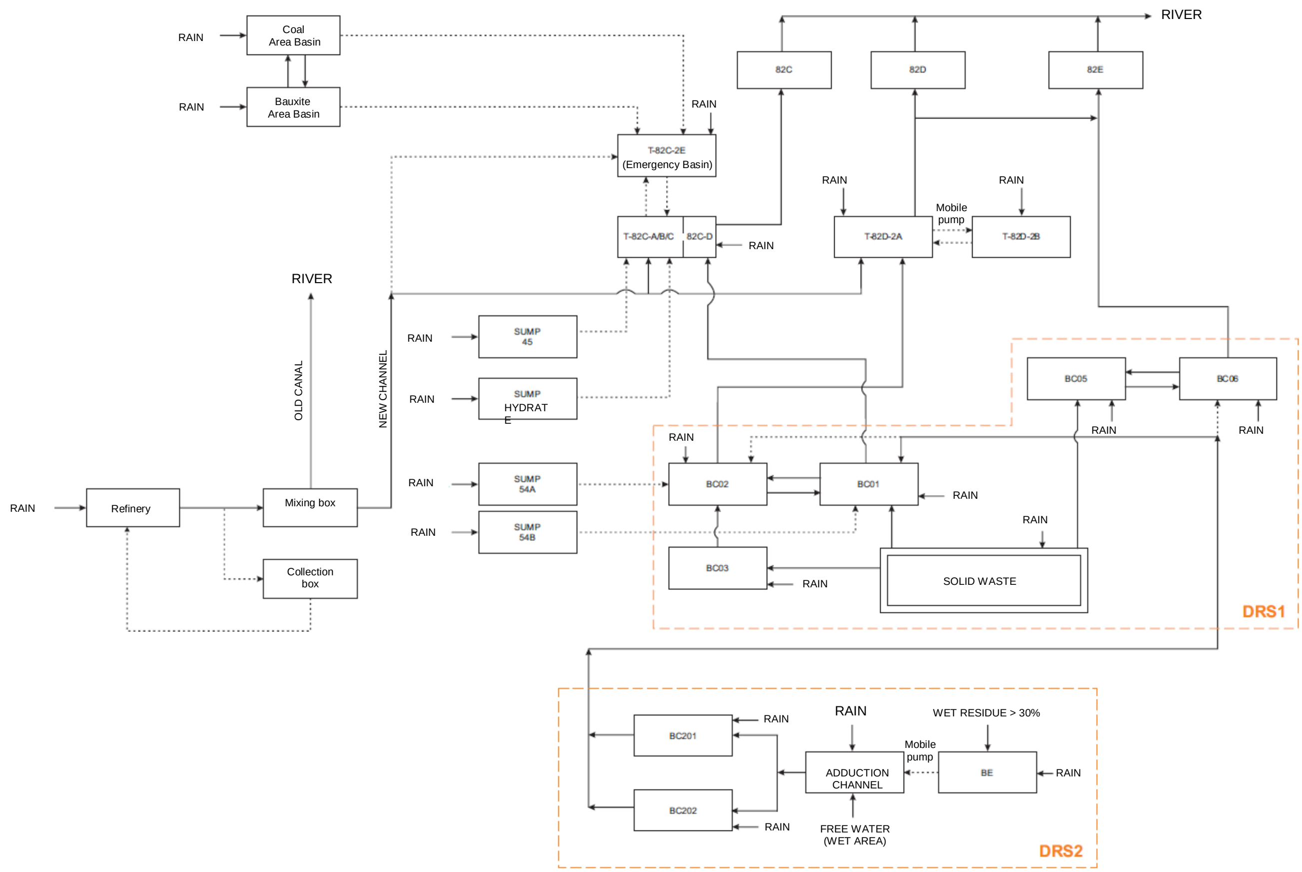


Figure 16 – PFD wastewater circuit in February 2018.

The new setup of Alunorte's wastewater circuit planned for May 2019, deadline of the project, in addition to the new basin T-82F-2A/B/C, it will include a new ETEI, 82F. The initiatives included in the project are intended to make the wastewater treatment system capable of handling extreme rainfall based on phenomena of climate change, bringing greater flexibility for existing plants 82C, 82D and 82E. Figure 18 presents the final PFD of the water management project.

The main difference between the PFDs of December 2018 and May 2019 is the new wastewater treatment plant (82F) and the wastewater distribution system, responsible for directing feeds of wastewater treatment units, in addition to increasing the transfer capacity of the pumping stations. According to figure 15, it is possible to observe a greater possibility of maneuvering between the basins, for example, DRS2, in addition to direct its wastewater to BC06, it is capable of pumping to T-82F-2A/B/C. Table 13 and Table 14 feature the new treatment and pumping capacity. The volumes of the basins will remain equal to the scenario of December 2018.

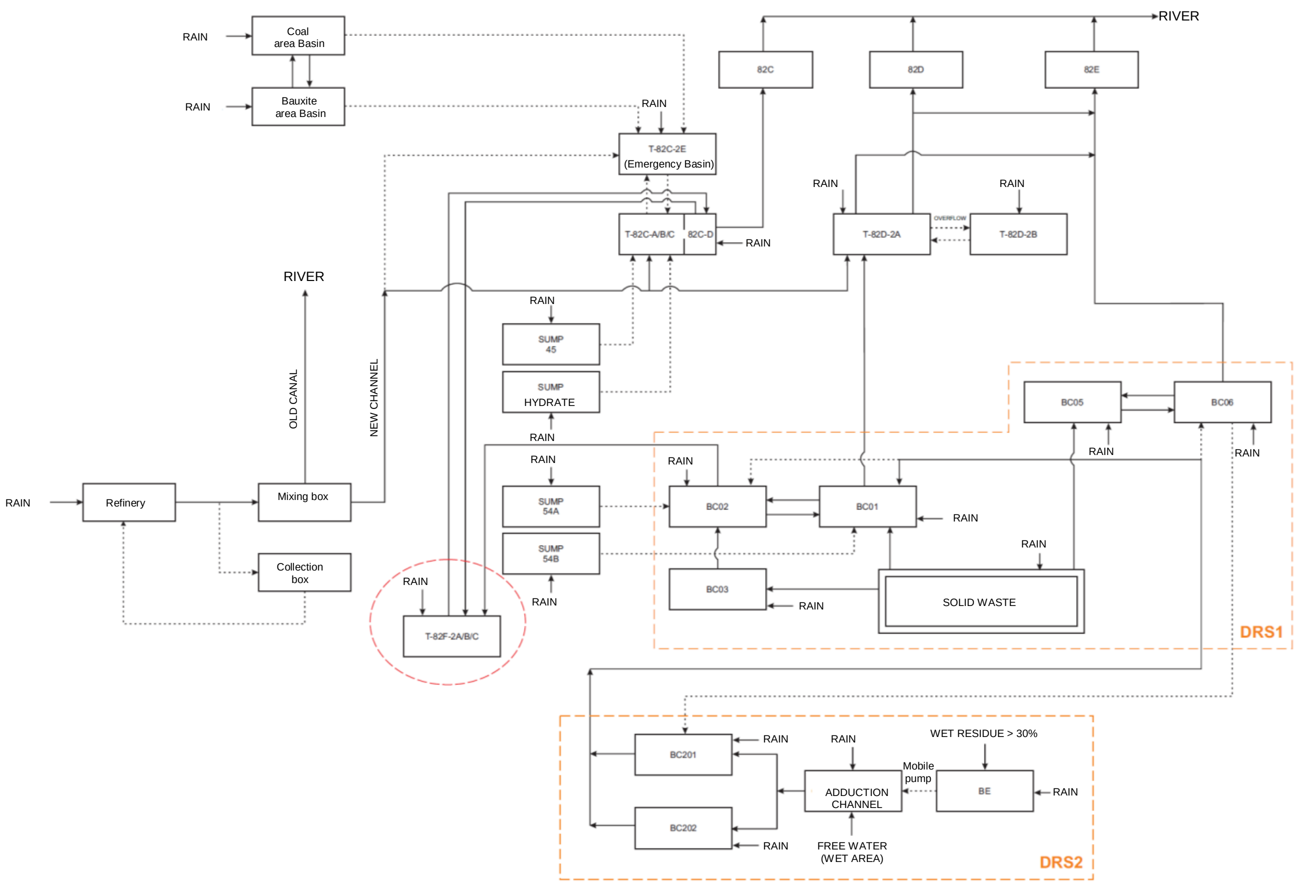


Figure 17 – PFD wastewater circuit in December 2018.

Table 11 - Volume of Basins in December 2018.

Basins	Total volume (m³)	Effective volume (m³)	Source
T-82C-2ABCD	48,961 *	39,168	Pimenta de Ávila Report
T-82C-2E	42,377 *	33,901	Pimenta de Ávila Report
T-82D-2AB	62,494 *	49,995	Pimenta de Ávila Report
T-82F-2ABC	274,340	227,122 **	Pimenta de Ávila Report
Coal and bauxite areas	27,663	22,130	Pimenta de Ávila Report

* Including the volume increased by the inclusion of *big bags*. ** Considering a silting of 17%.

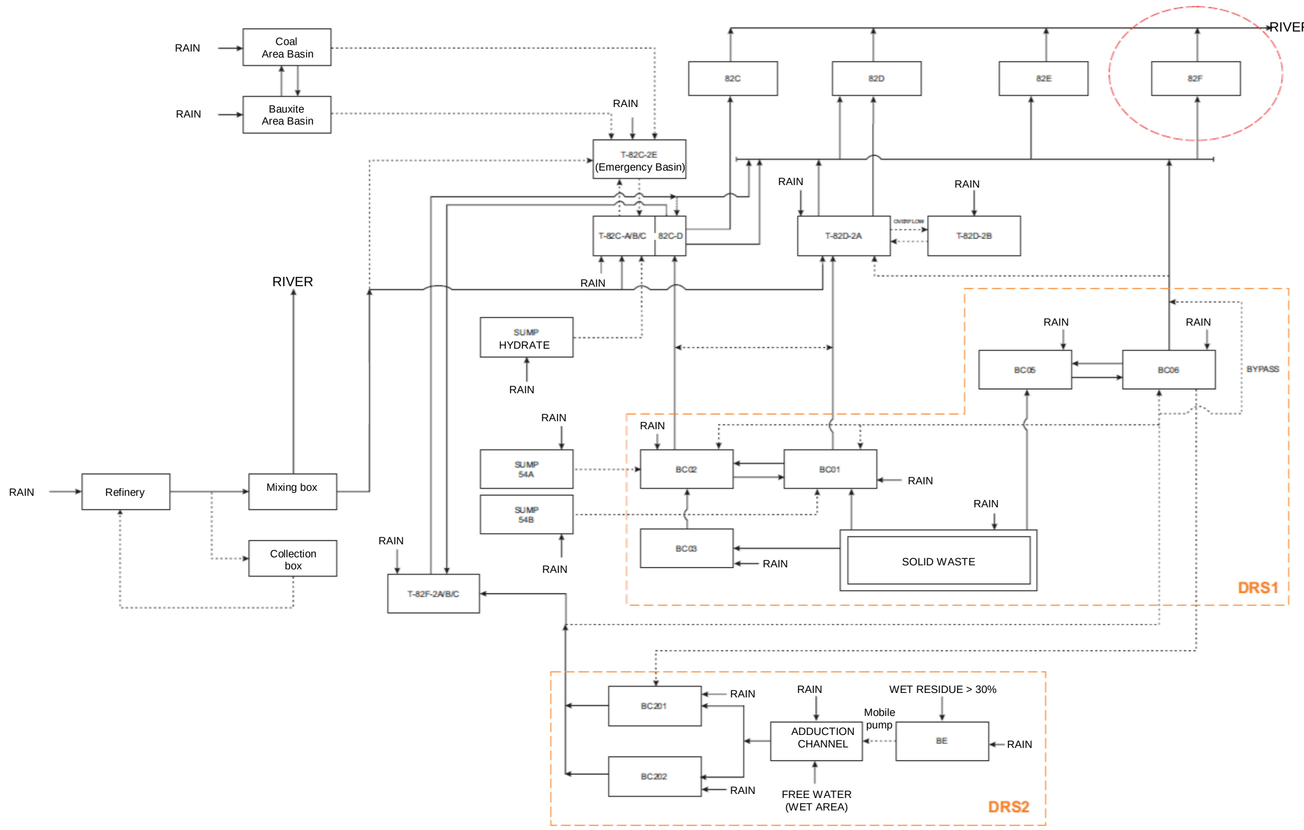


Figure 18 – PFD wastewater circuit in May 2019.

Table 12 - Pumping Capacity in December 2018.

Origin	**Destination**	**Flow (m³/hr)**
BC-201/BC-202	BC-1/2/6	3,100
BC-6	82E	3,100
Line (T-82D -> 82D)	82E	3,000
Sump Hydrate	T-82C	800
Sump-54A	BC-02	3,700
Sump-54B	BC-01	1,000
Sump-45	82C	1,000
Coal and bauxite areas	Emergency basin	5,500
BC-01	T-82D	3,050
BC-02	T-82F	3,250
T-82F	T-82C	4,500
T-82C	T-82F	17,792
BC-6	BC-201	1,000

Table 13 - Sumps basins catchment area in December 2018 and May 2019.

Basin/*Sump*	Catchment area (m²)			Source
	Feb/2018	Dec/2018	May/2019	
Sump Hydrate	153,000	23,444	23,443	Pimenta de Ávila Report
T-82C	37,000	166,556	166,556	Pimenta de Ávila Report
Sump-45	199,000	28,025	-	Pimenta de Ávila Report
T-82F-2A/B/C	-	170,975	199,000	Pimenta de Ávila Report
T-82D	16,000	16,000	16,000	Pimenta de Ávila Report
T-82C-2E	19,000	19,000	19,000	Pimenta de Ávila Report

Table 14 - Processing capacity in May 2019.

ETEI	Nominal Capacity	Operational Capacity	Source
ETE-82C	3600	3,240	CD394097Z001
ETE-82D	2800	2,520	CD394097Z001
ETE-82E	3100	2,790	CD394097Z001
ETE-82F	4500	4,050	CD394097Z001

Table 15 - Pumping Capacity in May 2019.

Origin	Destination	m³/hr
BC-201/BC-202	BC-1/2/6	3,100
BC-6	82E	3,500
Sump Hydrate	T-82C	800
Sump 45	T-82C	-
Sump 54A	BC-02	3,700
Sump 54B	BC-01	1,000
Coal and bauxite areas	Emergency basin	5,500
BC-01	T-82D	4,200
T-82F	T-82C	8,150
T-82C	T-82F	17,792
BC-6	BC-201	3,730
BC-02	82C	3,250
BC-201/BC-202	T-82F	2,870
Line (BC-02-> 82C)	Line (T-82D -> 82D)	3,250
Line (BC-6-> Header)	T-82D	3,570
BC-6	Header	3,500
82D	Header	3,725
82C	Header	3,725
82F	Header	8,150

Refinery Outflow

The outflow generated at the refinery is one of the variables needed to simulate the behavior of the system that involves Alunorte's wastewater. Since this variable is not measured directly, it was calculated by mass balance from the historic data of treated wastewater.

The wastewater to be treated is generated from four main sources: refinery wastewater, DRS1 wastewater from, DRS2 wastewater and rainwater. The contribution of rainwater was isolated using the historic data of rainfall. According to the technical team of Alunorte, ETEI efficiency is 90%, considering that the bottom of the wastewater processing tanks is directed to the DRS1, so that the refinery outflow was estimated by the equation below.

$$Q_{EF} = \frac{Q_{ET} - Q_C}{0,9}$$

Where

Q_{EF} = industrial wastewater outflow, in m^3/h;

Q_{ET} = treated wastewater released into the River outflow, in m^3/h;

Q_C = rain outflow, in m^3/h.

It is important to emphasize that the above formula is conservative, because it considers that all rain water to fall in the refinery, acquires the characteristic of wastewater, disregarding absorption and/or natural evaporation, for example. To estimate the average outflow of industrial wastewater from the refinery operating at 100% capacity, we used historical data of release of wastewater from 2017. For operation at 50%, it was considered the historical data for the period between March and October 2018.

The rain outflow was calculated from historical data of rainfall in the region, which were informed by Alunorte. Considering all the rain that falls on the area of the refinery, it was possible to estimate the average monthly outflow of rain water that is added to the industrial wastewater.

Figure 19 shows the history of outflow during 2017, where it is estimated an average outflow equal to 2327.2 m^3/h. Figure 20 shows the monthly rainfall during 2017, where it is possible to calculate the cumulative figure of 2650 mm throughout the year. Upon dividing the total number by 8760 hours, we have:

$$P_{média} = \frac{2650\,mm}{8760\,h} = 0,302534\,mm/h$$

To estimate the volume of rain that corresponds to the treated wastewater, the catchment area of rain was considered as being:

$$A_{Total} = A_{Refinaria} + A_{DRS1} + A_{DRS2} = 5.307.137\, m^2$$

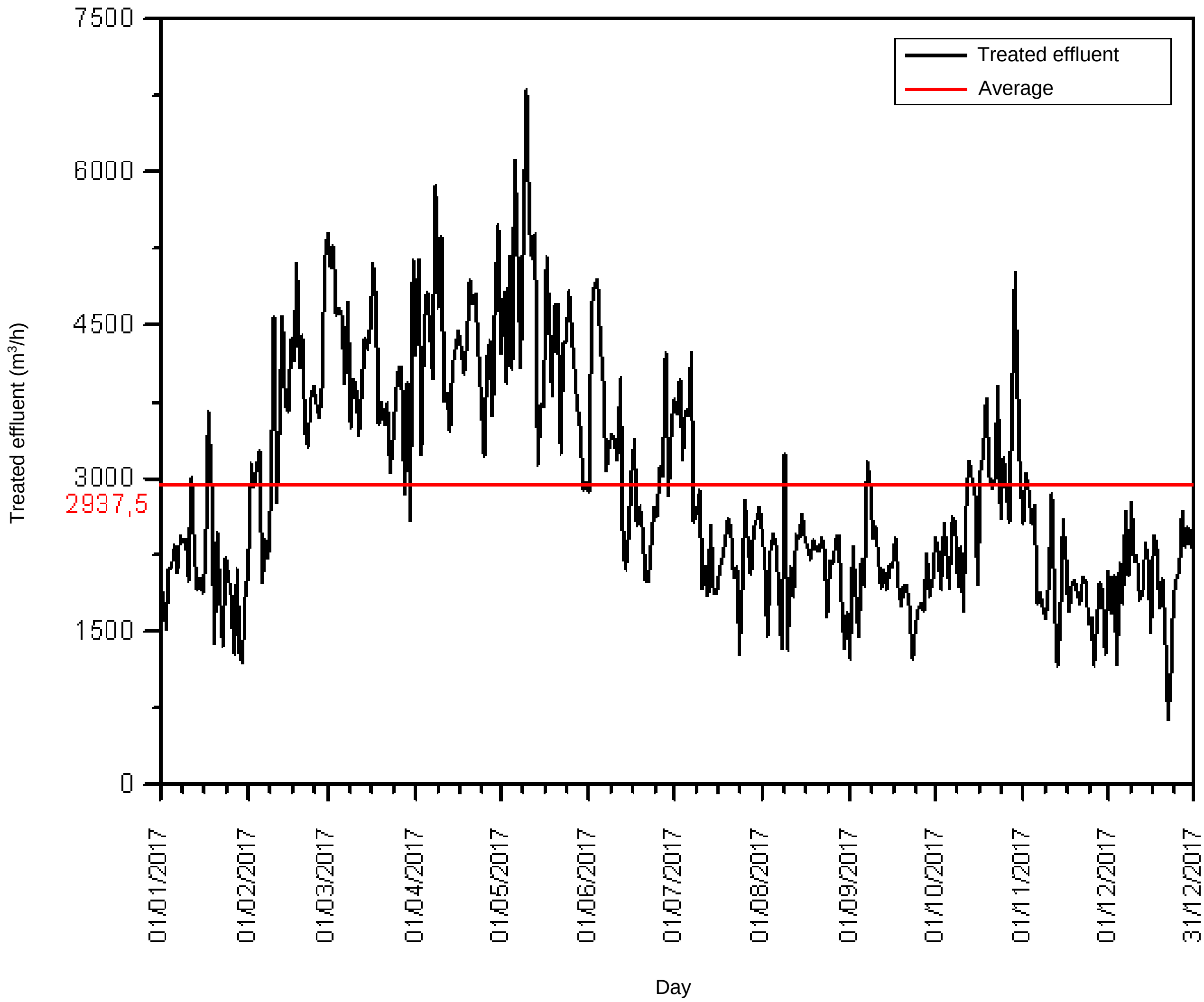


Figure 19 - Daily Outflow of treated wastewater in 2017.

Therefore, the volumetric outflow of rain water which is part of the wastewater during 2017 is given by the equation below (INMET, 2018):

$$Q_C = A_{Total} x \frac{P_{média}}{1000} = 1605{,}6\ m^3/h$$

Where the value 1000 is the conversion factor from mm to cubic metre.

In this way, we have that, on average, from each 2937.5 m³/h of treated wastewater, 1605.6 m³/h corresponds to rain water. Therefore, one can estimate the average outflow of wastewater produced to the refinery operating at 100% capacity:

$$Q_{EF}(2017) = \frac{Q_{ET} - Q_c}{0{,}9} = \frac{2937{,}5 - 1605{,}6}{0{,}9} = 1479.9 m^3/h$$

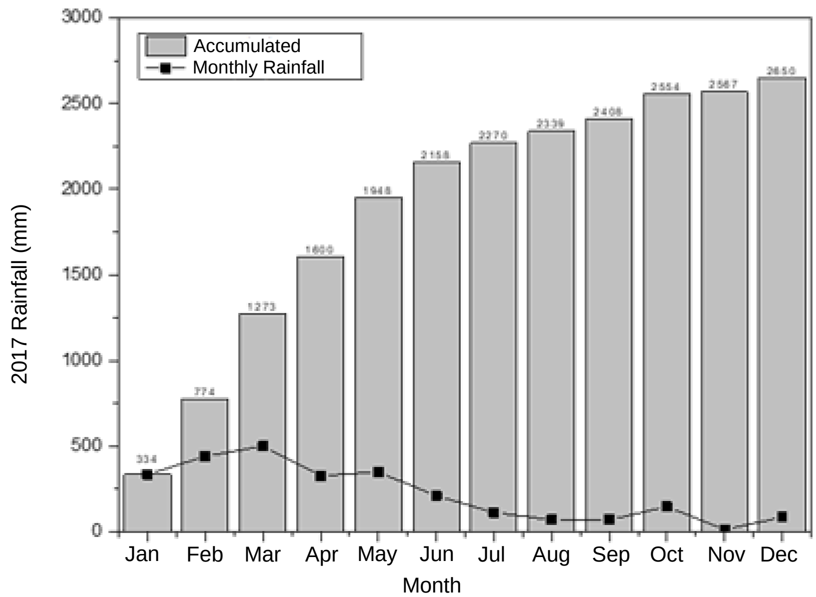


Figure 20 - Rainfall in 2017.

Figure 21 shows the history of outflow between March and October 2018, during which time the refinery operated at 50% capacity. From this history, one can estimate an average flow of 3672.1 m³/h of treated wastewater. Figure 22 shows the monthly rainfall during the same period, from which it is possible to calculate the total of 1979.4 mm. Upon dividing the total number by 8760 hours, we have:

$$P_{média} = \frac{1979{,}4 mm}{5880\, h} = 0{,}336632 mm/h$$

Therefore, the volumetric outflow of rain water which is part of the wastewater during 2017 is given by the equation below (INMET, 2018):

$$Q_C = A_{Total} x \frac{P_{média}}{1000} = 1786{,}55\ m^3/h$$

In this way, we have that, on average, from each 3672.1 m³/h of treated wastewater, 1785.55 m³/h corresponds to rain water. Therefore, one can estimate the average outflow of wastewater produced to the refinery operating at 50% capacity:

$$Q_{EF}(2018) = \frac{Q_{ET} - Q_c}{0{,}9} = \frac{3672{,}1 - 1786{,}5}{0{,}9} = 2095{,}1 m^3/h$$

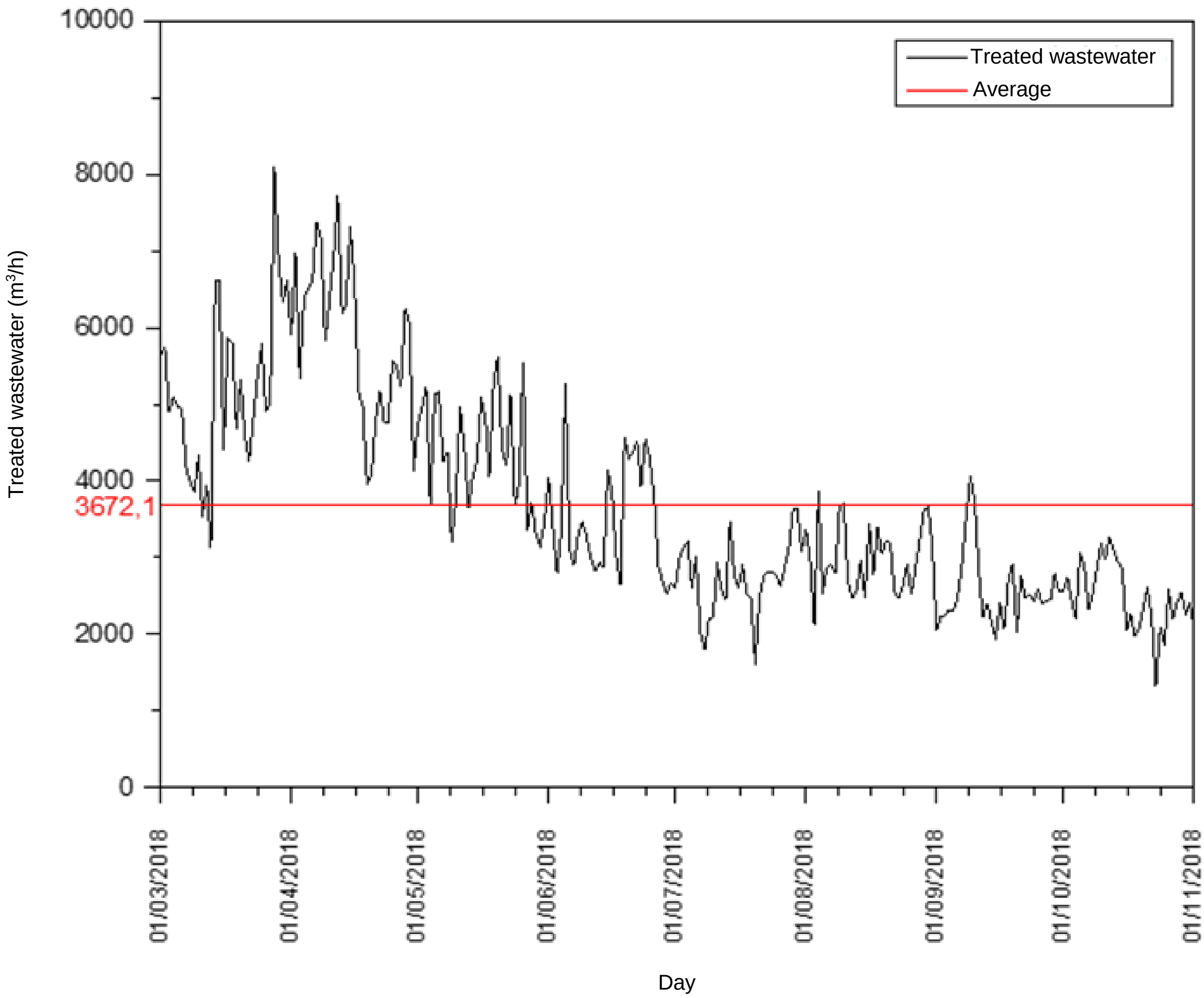


Figure 21 - Treated wastewater daily outflow between March and October 2018.

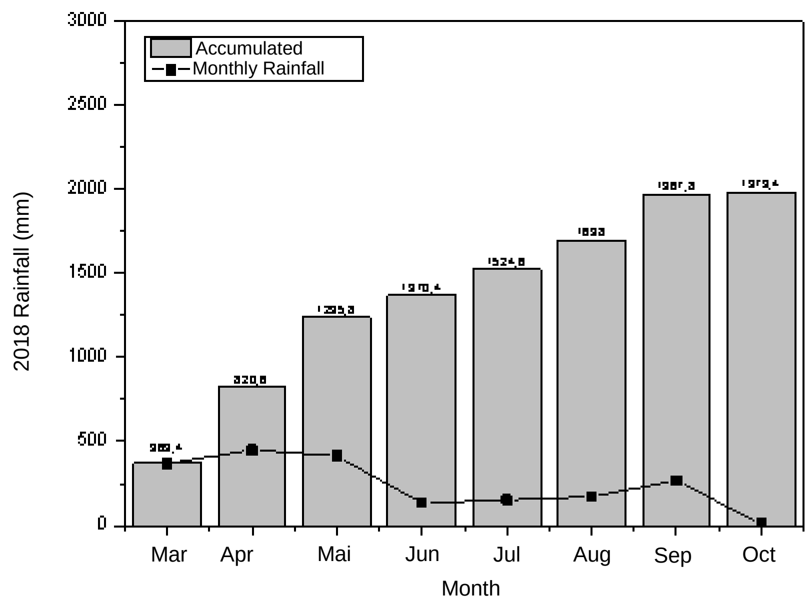


Figure 22 - Rainfall in 2018.

In the expert literature, only the report *Water Requirements of the Aluminum Industry,* written by Howard Conkum in 1956, studies the use of water in aluminum plants; and concludes, on pages 103 and 123, that the production capacity, isolated, has little effect on the needs and use of water and, consequently, in the generation of wastewater from the production process.

As it can be evidenced on pages 122 and 123 of the above-mentioned report, the study was conducted in 6 plants in the United States, which were divided into two groups according to the production capacity. Group 1 was formed by the smaller plants that produced around 900 tons/day of alumina, while Group 2 was composed by the larger plants and had double the production capacity of the smaller plants. As a result of the study, it was found that the smaller plants used as much water for alumina produced than larger plants.

The assumption that the increase in production capacity has little effect on the water balance of the plant was confirmed by the study, and the author assigns the variation of the amount of water in the plant to factors such as the amount of annual rainfall in the area of disposal of bauxite residue.

The simulations were carried out considering the 2 (two) values calculated for the outflow: 1,480 and 2,100 m^3/h. Obviously, these values are estimates, since the basin level varies throughout the year. However, the assessment of most of the scenarios, especially those of the future, was performed considering the greatest value, 2,100 m^3/h; that is, most of the findings were obtained based on a conservative operating condition.

It is also important to emphasize that the outflow of water generated by the rain did not take into account the absorption by soil, i.e. all rainwater was transformed into rainwater outflow; another conservative decision for the evaluation of scenarios.

Return Period – On the rainfall that took place

The term return period or recurrence is the average interval of time (usually given in years) when certain hydrological event can occur or be overcome. The return period (*TR*) is also the inverse of the probability of an event to be equaled or exceeded, where this probability (*p*) of occurrence is calculated based on historical series observed at the site.

$$TR = \frac{1}{p}$$

From the return period, it is possible to calculate the intensity, defined as the amount of rainfall in a given unit of time. For the calculation of the intensity, the equation of heavy rain for the city of Barcarena was used (Souza *et al.*, 2012), which expresses the relationship between intensity, duration and frequency from the following equation.

$$I = \frac{1007{,}3605 x\, TR^{0{,}107}}{(t + 9{,}7931)^{0{,}7243}}$$

Where,

I – Intensity of rainfall in mm/h;

TR - Return period in years;

t - rain duration in minutes.

The results obtained from the equation of heavy rains, allow the construction of a table relating the duration with the intensity of the rainfall event, in mm/h, for the municipality of Barcarena, whose result is shown in Table 16.

According to Alunorte's rainfall data, between February 16 and 17, 2018 there was a rainfall of about 231.20 mm in 12 hours, thus providing an average intensity of 18.87 mm/h. Thus, from the rainfall data of the day of the hydrological event, combined with the results obtained by means of the equation for heavy rains for the city of Barcarena, it can be concluded that the hydrological event occurred between February 16 and 17 of presents a return period of 2,500 years, as shown in Table 16.

According to the SEMAS-PA, the average rainfall for the month of February is 370.9 mm, as shown in Figure 23; therefore, according to these data, at an interval of 12 hours it rained 62.3% of the forecast for the entire month of February 2018.

For the simulation of scenarios before and after the modifications carried out or in progress in the waste management system of Alunorte, it was also considered a rainfall as shown in Figure 23, that, according to the company's weather station, it was the rainfall that occurred between the evening of February 16 and the morning of 17, 2018. As previously mentioned, the average rainfall during the event was 18.87 mm/h; however, it is essential to emphasize that the results obtained for scenarios of rainfall using the profile in Figure 24 is completely different from that using the average.

On the other hand, the CPRM report, issued in March 2018, says that in the 48 hours of February 16 and 17, 2018 it rained 74.1 mm, according to Vila do Conde's rainfall station gauge measurements (ANA 00148011). In this way, it was also carried out a simulation of a scenario with this average precipitation.

Table 16 – Intensity of heavy rainfall for the municipality of Barcarena.

	INTENSITY (mm/h)									
DURATION	**10**	**20**	**50**	**100**	**200**	**500**	**1,000**	**2,500**	**5,000**	**10,000**
5 min	183.11	197.21	217.52	234.27	252.30	278.29	299.72	330.59	356.04	383.45
10 min	148.29	159.71	176.16	189.72	204.33	225.38	242.73	267.73	288.34	310.54
15 min	125.97	135.67	149.64	161.17	173.57	191.45	206.19	227.43	244.94	263.80
20 min	110.28	118.77	131.00	141.09	151.95	167.60	180.50	199.10	214.42	230.93
25 min	98.56	106.14	117.08	126.09	135.80	149.79	161.32	177.93	191.63	206.39
30 min	89.42	96.31	106.23	114.40	123.21	135.90	146.37	161.44	173.87	187.26
45 min	70.93	76.39	84.26	90.75	97.73	107.80	116.10	128.06	137.92	148.53
1 hour	59.53	64.11	70.71	76.16	82.02	90.47	97.43	107.47	115.74	124.66
1.5 hours	45.94	49.48	54.58	58.78	63.31	69.83	75.20	82.95	89.34	96.21
2 hours	37.98	40.90	45.12	48.59	52.33	57.72	62.17	68.57	73.85	79.53
3 hours	28.84	31.06	34.26	36.90	39.74	43.83	47.21	52.07	56.08	60.40
4 hours	23.64	25.46	28.08	30.24	32.57	35.93	38.69	42.68	45.96	49.50
6 hours	17.79	19.16	21.13	22.76	24.51	27.04	29.12	32.12	34.59	37.26
8 hours	14.51	15.63	17.24	18.57	20.00	22.06	23.76	26.21	28.22	30.40
10 hours	12.38	13.34	14.71	15.84	17.06	18.82	20.27	22.36	24.08	25.93
12 hours	10.87	11.71	12.92	13.91	14.98	16.53	17.80	19.63	21.14	22.77
14 hours	9.74	10.49	11.57	12.46	13.42	14.80	15.94	17.58	18.94	20.39

24 hours	6.61	7.12	7.86	8.46	9.11	10.05	10.83	11.94	12.86	13.85
2 days	4.01	4.32	4.77	5.13	5.53	6.10	6.57	7.25	7.80	8.40
3 days	2.99	3.22	3.56	3.83	4.13	4.55	4.90	5.41	5.82	6.27
5 days	2.07	2.23	2.46	2.65	2.85	3.15	3.39	3.74	4.02	4.33
10 days	1.25	1.35	1.49	1.60	1.73	1.90	2.05	2.26	2.44	2.62
15 days	0.93	1.01	1.11	1.20	1.29	1.42	1.53	1.69	1.82	1.96
20 days	0.76	0.82	0.90	0.97	1.05	1.15	1.24	1.37	1.48	1.59
25 days	0.65	0.70	0.77	0.83	0.89	0.98	1.06	1.17	1.26	1.35
30 days	0.57	0.61	0.67	0.72	0.78	0.86	0.93	1.02	1.10	1.18

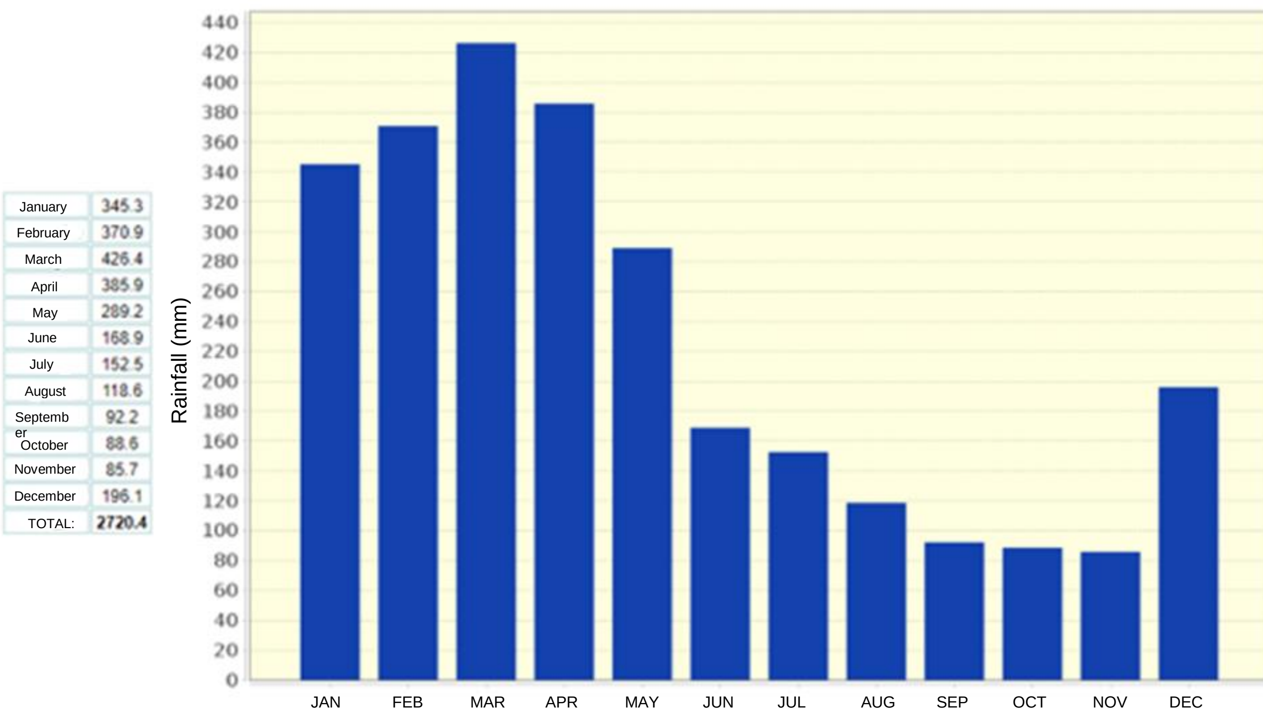


Figure 23 - Monthly Average Rainfall in the city of Barcarena (1970 to 2007). Access on 11/05/2018, at 16:18
http://seirh.semas.pa.gov.br:81/SISMET/faces/climatologico/

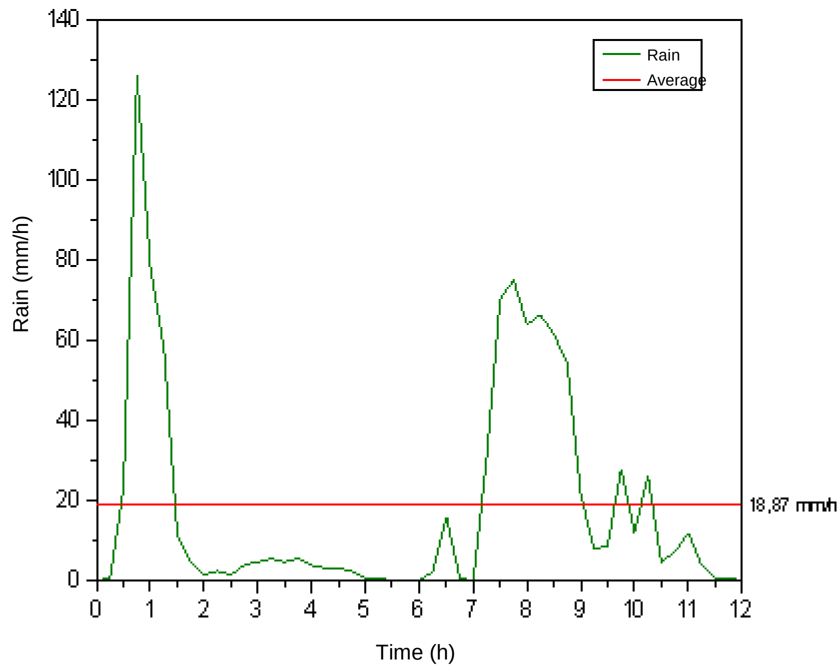


Figure 24 – Rain profile February between 16 and 17, 2018, according to Alunorte's rainfall station.

The discrepancy between Alunorte's and CPRM's information on the rainfall occurred on February 16 and 17, 2018 is significant, so that all the details involving the obtaining of such information should be considered. For example, in Vila do Conde's Rainfall Station, the location mentioned by CPRM for obtaining the rainfall volume, the reading is performed manually once per day, while at Alunorte's rainfall station reading is performed automatically and computed in 15 min intervals. Another point to be highlighted is the distance between the two rainfall stations; about of 5 km, which is a considerable distance when it comes to weather, especially in conditions of extreme rainfall and concentrated in small areas.

Regarding the specification of the return period to define the size of overflow systems and other hydraulic structures, there is no mention in Federal Law n. 12.334 of 2010 (National Dam Safety Policy), nor in Normative Instruction SEMAS n. 02/2018 (Safety Plan for Water Accumulation and Industrial Waste Disposal Dams).

On the other hand, NBR 13028 of 2017 establishes criteria for preparation of mining dams projects, while NBR 13029 of 2017 establishes the criteria for the preparation of projects regarding sterile disposal in the stack. By definition, Alunorte's DRSs would not be included in any of the above descriptions, but due to the absence of other standards, both can be considered "good practices".

NBR 13028 states that the overflow systems of geotechnical structures with high Potential Damage must be set for a return period of 1,000 years or more, during the operational period of the structure. The return period rises to 10,000 years or above for the period of structure closure.

The classification with regard to the potential damage of the Alunorte's DRSs should be on Normative Instruction SEMAS n. 02/2018, pursuant to Federal Law n. 12.334 of 2010.

Implementation in Aspen

The Aspen™ Simulator solves many of the critical issues of engineering, as well as operational problems that appear throughout the life cycle of a chemical process, such as: design of a new process, research of the effects of a unit on the whole process or the optimization of operations of a complete process.

Aspen™ capabilities enable engineers to predict the behavior of a process using basic relations of Engineering: mass and energy balances, phase and chemical equilibrium and kinetics of reactions.

Aspen™ has a graphical interface that allows the user to view all stages of the process being evaluated, as well as all the input data being entered by the user, allowing for better understanding of the process being simulated. The simulator has a large number of physical properties, data models and assessment methods that cover much of the simple and ideal behavior processes, as well as the processes with non-ideal mixtures. The simulator also makes a convergence analysis that considers automatically and suggests optimal cuts in the flow, methods of convergence of the PFD and the solution to most of the PFDs with data recirculation. Aspen™ is able to do a sensitivity analysis to generate, conveniently, tables and graphs showing how the performance of the process varies with changes made in the specifications of the equipment and selected operation conditions. Through the project specifications, the simulator calculates operating conditions or parameters of equipment to find the desired performance.

The resolution of the flowcharts in Aspen™ is characteristically performed in sequential modular mode, that is, each block is resolved at a time (mass and energy balances), so that the output (result) of a block will be the input (data) of the following. The simulator must receive the necessary information about the flowchart to perform the calculations using mathematical models that are embedded in each block. The amount of information needed for a particular block is fundamental to allow a simulation to run, so that the number of information depends on the degrees of freedom of each block.

Figures 25, 26 and 27 show the PFDs in Aspen Dynamics™ for the following situations: February 2018, December 2018 and May 2019, respectively.

The PFDs in Aspen™ have been implemented from the PFDs shown earlier, which were validated by Alunorte's project documentation.

In figures 25, 26 and 27 each "square" represents a basin or *sump* at Alunorte, while each row represents the connection pipe between the water, or a stream of rain. Basins and *sumps* were implemented considering the volumetric capacity, pumping and treatment capacity, whose values are given in item 5, as referred to in project and informed by Alunorte. The rain outflow generated for basins, *sumps* and DRSs by rainfall was also described previously.

With the PFDs of figures 25, 26 and 27, it is possible to predict the behavior of variables such as level and outflow as a function of time.

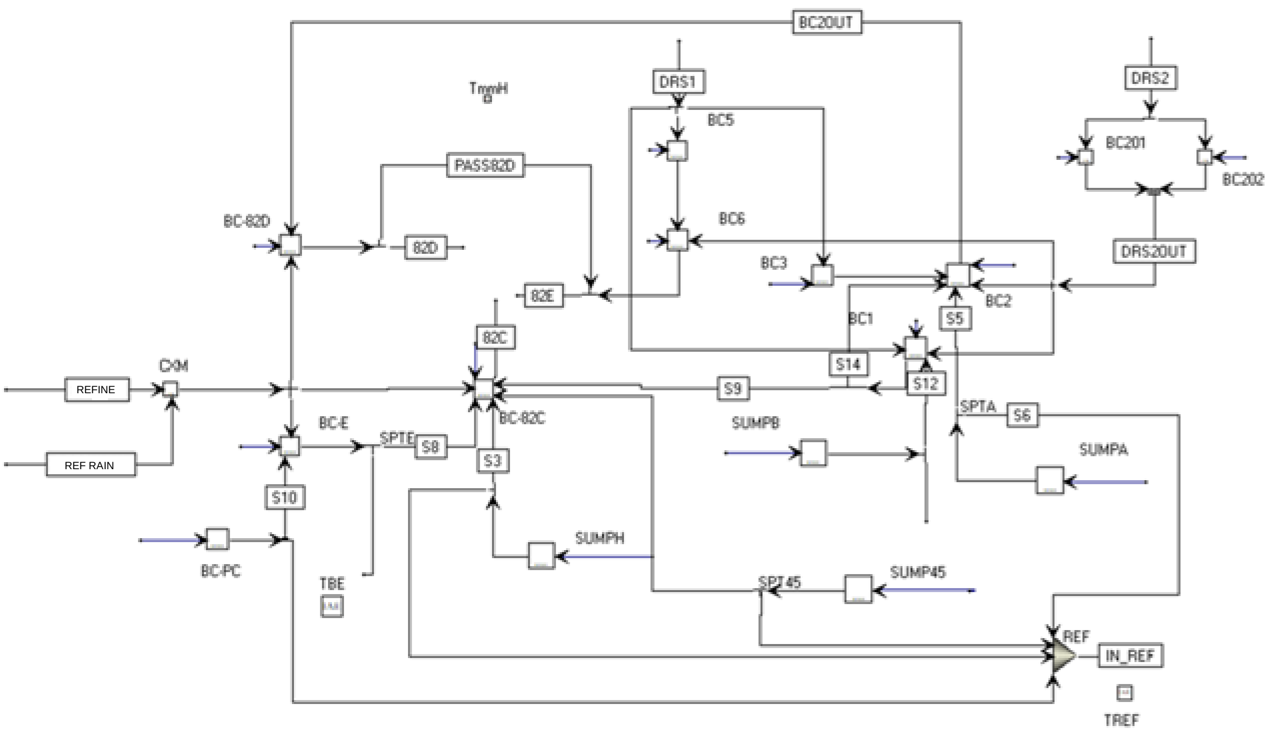


Figure 25 - Process flowchart for February 2018.

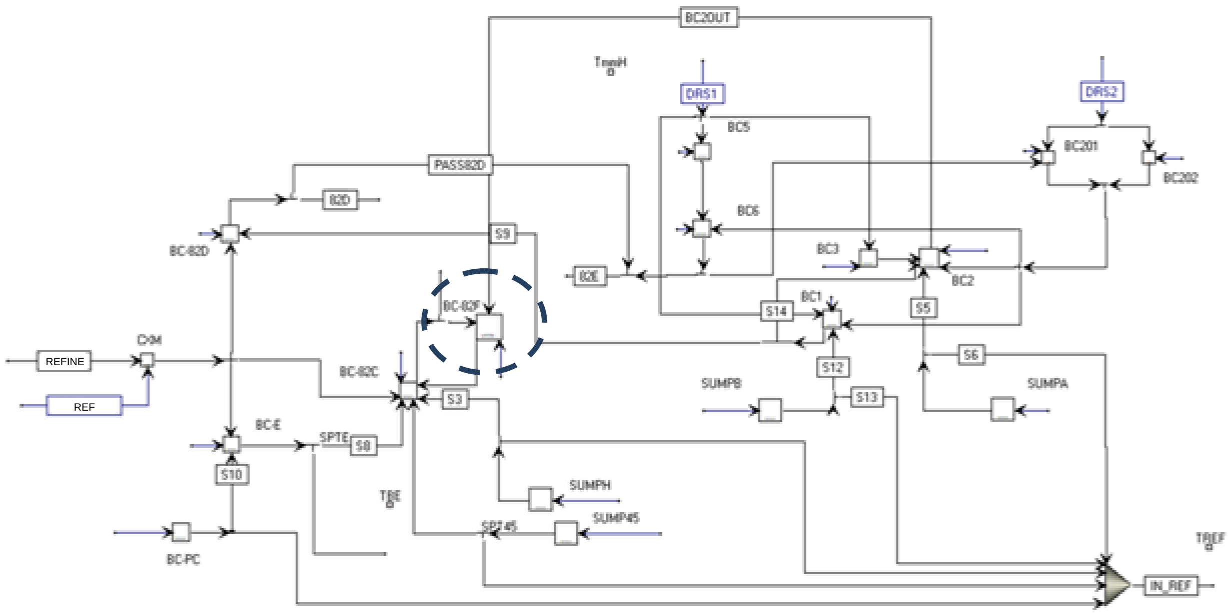


Figure 26 - Process flowchart for December 2018.

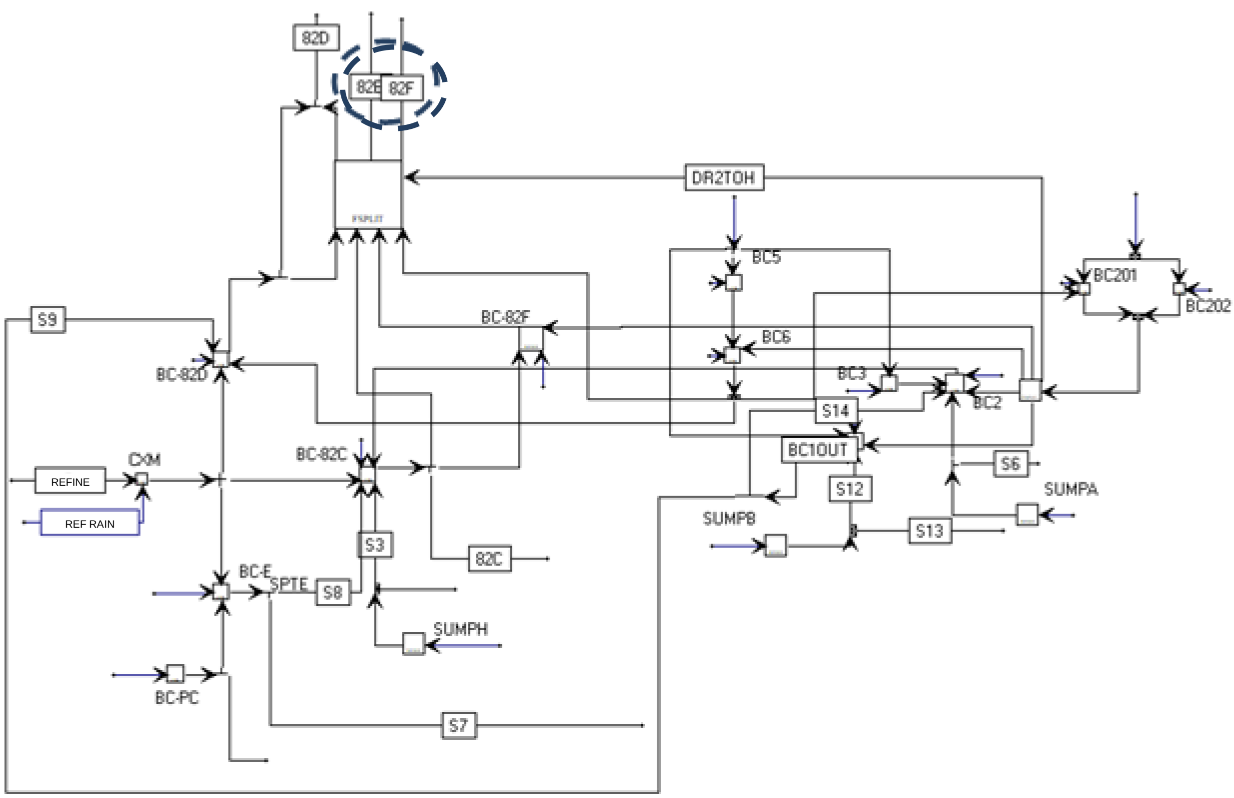


Figure 27 - Process flowchart for May 2019.

In the transient regime, whose variables change with time, ordinary differential equations (ODE) resulting from the implementation of PFDs in Aspen Dynamics™ are resolvedsimultaneously using the Implicit Euler method, with variable pace; in fact, this is a problem of initial value (PVI), whose initial value for each differential variable is obtained through simulation in stationary regime, which come from the Aspen Plus™ simulation. In other words, the system is initially modeled on stationary regime (Aspen Plus™) and then exported to the transient regime (Aspen Dynamics™).

The equation below shows the mass balance applied to a basin/*sump*:

$$F_{in}\rho_{in}\Delta t - F\rho\Delta t = M_{t+\Delta t} - M_t$$

Where:
F = volumetric flow rate
ρ = density
t = time
M = Mass
The right side of the equation represents the difference between the basin's input mass and toutput mass, while the right side represents the accumulated mass in the time interval t + Δt. Dividing both sides of the equality by Δt and applying the limit when that Δt tends to zero yields the differential equation below:

$$F_{in}\rho_{in} - F\rho = \frac{dM}{dt}$$

Knowing how the volume of the basin varies as a function of height (h), it is possible to turn the rate of change $\frac{dM}{dt}$ in $\frac{dh}{dt}$, so that it is possible to monitor the value of the level of the basin as a function of time. Figure 28 shows the behavior of some variables, including the level of various basins and *sumps,* on the screen of Aspen Dynamics™.

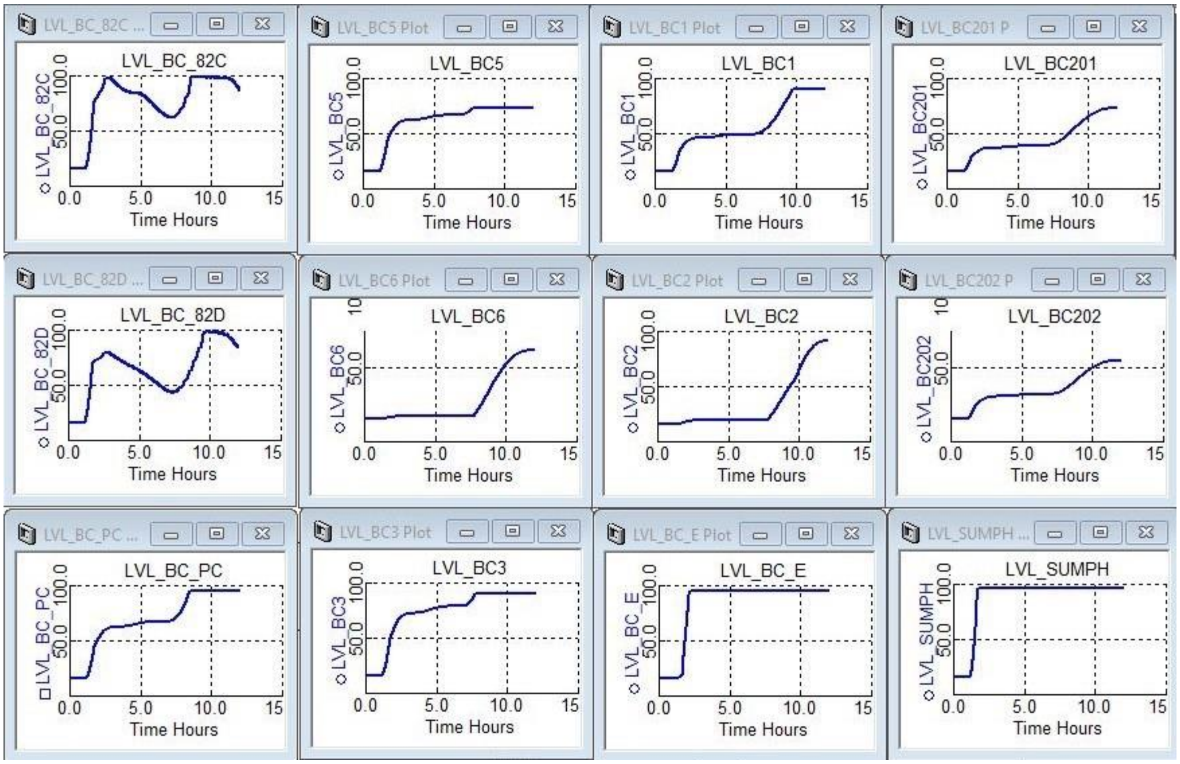


Figure 28 - Aspen™ screen showing the behavior of variables over time.

It is important to emphasize that the basin level varies according to the outflow that comes to it, as well as it depends on the operating procedure carried out by engineers and operators; and the outflow generated by rain, if it happens.

For the purposes of simulation, the initial value for the volume of basins and *sumps* was calculated considering 20% of siltation and, based on discussions with technicians from Alunorte, estimated an initial level of 10%. The operating procedure was programmed in the form of *tasks* and *constraints* (files with instructions), and Figures 29 and 30 show the Aspen Dynamics™ implementation, and it is described below for February 2018, December 2018 and May 2019, respectively.

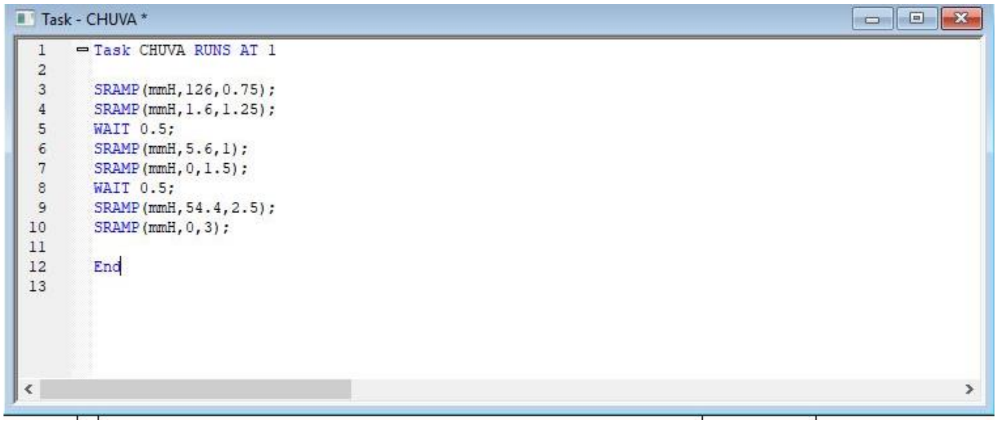


Figure 29 - *Command lines for implementation of a* task.

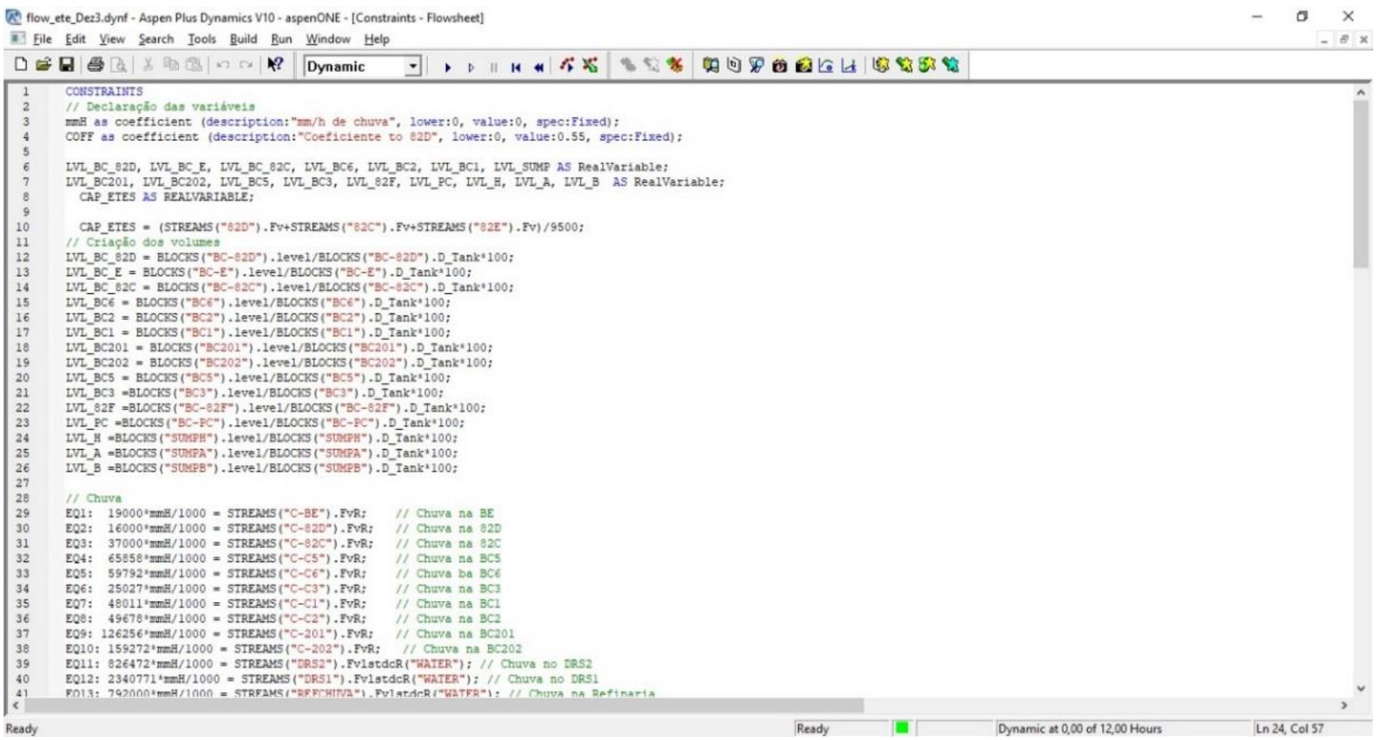


Figure 30 - Command lines for implementation of a constraint.

Assumptions for the simulation: February 2018 Scenario

a) When rainfall begins, the lines connecting the DRSs with the ETEI are blocked and, at the same time, the ETEIs are taken to their maximum capacity, a total of 9,500 m³/h (82C = 3,600 m³/h; 82D = 2,800 m³/h and 82E = 3,100). The increased treatment flow of the ETEI is carried out gradually and the time required to achieve the total capacity of treatment is of 1 hour.

b) If the level of the 82C basin reaches 80%, the floodgate of the emergency basin is open to send part of the water that would go to basins 82C and 82D; this floodgate stays open until the level of 82C reaches 50%.
c) It was considered that if rain water collected by *sumps* (45, hydrate, 54A and 54B) is less than their maximum outflow, the water is pumped to the destinations referred to in Alunorte's project. If the flow generated by rain is greater than the maximum outflow, pumping is performed to the maximum and the remainder of the volume of rain water will accumulate in the *sumps* (keeping the excess inside the refinery area).

Assumptions for the simulation: December 2018 Scenario

a) In the PFD of December there was the inclusion of basin 82F; in this case, in addition to the procedures described for the scenario of February 2018, it was added the condition that when the level of the basin 82C reaches 50%, the pumping to the basin 82F should start. According to Alunorte, pumping capacity for the basin 82F is 17,792 m³/h.

Assumptions for the simulation: May 2019 scenario

a) Due to the installation of new pipes, the number of maneuvers increases. In this way, a procedure as simple as possible was used in order to avoid points of operational complexity. In this PFD, ETEI treatment capacity is 14,000 m ³/h, due to the inclusion of a new ETEI (82F), with capacity of 4,500 m³/h.
b) When the rainfall begins, the lines connecting the DRSs with the ETEIs are blocked and, simultaneously, both ETEIs are taken to their maximum capacity within 1 hour; 7,000 m³/h are pumped from basin 82D, and the rest of basin 82C (7,000 m³/h).
c) Another important line is aligned withthe beginning of the rainfall; 17,792 m³/h are pumped from the basin 82C to basin 82F.
d) The *sumps* continue to be aligned as in the February 2018 scenario.

DRS1 and DRS2 basins are connected by channels, floodgates and overflow pipes. In this way, the logic implemented for both DRSs was that all the basins are closed so that only receive water from rain and that the release to the following basin occurs only when the level of the basin reaches 90%; right now, all the water that comes at that basin is transferred to the next basin.

The sequence of transfer of the basins:

a) When the level of basin BC05 reaches 90%, all the water that comes in it is directed to the basin BC06 (**DRS1**);
b) When the level of basin BC03 reaches 90%, all the water that comes in it is directed to the basin BC02 (**DRS1**);
c) When the level of basin BC01 reaches 90%, all the water that comes in it is directed to the basin BC02 (**DRS2**);

8. RESULTS FOR THE ASSESSED SCENARIOS

Once the model is validated, according to the number of variables, it is possible to assess thousands of operational scenarios; with and without rainfall (rain). In this sense, the first scenario studied was February 2018; more specifically, the scenario between the end of the 16 and the morning of the 17.

It is worth noting that the rain represents a single variable in the modeling; however, once that occurs, this variable is associated with all the other variables, including the pipes that form Alunorte's wastewater drainage, pumping and treatment system.

For all scenarios, the simulation starts without the occurrence of rainfall; then, at time t = 1:00, the rain starts.

Among the possible scenarios, those who could answer as many issues related to handling and generation of wastewater were chosen:

- Treatment system;
- Pumping system;
- Volumetric storage;
- Operation of the plant.

We evaluated the following scenarios:

1. Reproduction of the February 2018 event, with the refinery generating 1,480 m^3/h (100% production) wastewater and PFD of February 2018;
2. Refinery initially generating 1,480 m^3/h and then 2,100 m^3/h wastewater, without rain and PFD of February 2018;
3. Refinery generating 2,100 m^3/h wastewater, considering the February 2018 rain, new basins and sumps catchment areas, new pumping capacity and PFD of December 2018;
4. Refinery generating 2,100 m^3/h wastewater, considering average rainfall of 22.77 and 12.86 mm/h, for 12 and 24 hours, respectively, new basins and sumps catchment areas, new pumping capacity and PFD of December 2018;
5. Refinery generating 2,100 m^3/h wastewater, considering average rainfall of 22.77 and 12.86 mm/h, for 12 and 24 hours, respectively, new basins and sumps catchment areas, new pumping capacity and PFD of May 2019;

As it can be seen, most scenarios evaluated considered the greatest value for the outflow generated by the refinery, which means a more conservative decision in carrying out this study.

Scenario 1 – Reproduction of the February 2018 event, with the refinery generating 1,480 m^3/h (100%) wastewater and considering the PFD of February 2018

For the simulation of the February 2018 scenario, a PFD for that period was used, as shown in the previous item. This scenario simulation aimed to validate the model implemented in Aspen™, observing the behavior of the level of basins and *sumps* before the rain on February 16 and 17, 2018.

Figure 31a shows the level of ETEI basins, bauxite and coal areas, DRS2 and DRS1. The dashed line in the vertical direction shows the moment in which the rain starts, whose intensity has been shown in Figure 24.

As it can be seen in Figure 31a, in less than 1:00 the basins of the coal and bauxite areas have reached their maximum limit. The basins of area 82 only reached their maximum levels about 8:00 after the rain. It is important to emphasize that the behavior of the levels of the area 82 basins, increasing and decreasing, is directly related to the profile of the rain and the percentage of treatment capacity; for example, the decrease in the level between 2 and 7:00 is due to decreased rainfall and increased flow of treatment. However, after 8:00 of rainfall, wastewater treatment capacity was not sufficient and the basins of area 82 reached their limit.

At this point, it is important to note that the level of the basin or *sump* constant at 90%, implies that the wastewater is flowing to or being pumped into another basin.

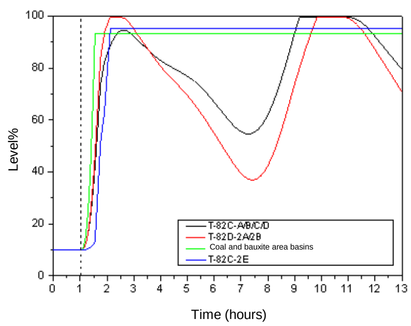
Figure 31d shows that, with the exception of 54B, all *sumps* overflowed in less than 1:00; this can be explained by insufficient storage capacity and/or pumping, when faced with the volume of rainfall considered.

Figures 31b and 31c show that the levels of DRS1and DRS2 basins, respectively, have increased, but not overflowed. For the basins DRS1 BC02 and kept the BC06 level below 80%; BC01 basins, BC03 and BC05, reached the maximum of 90%, because from that value the effluent was poured for BC02 or BC06. For the DRS2, the basin level did not even reach 80%; BC-202 level, which is the largest and can receive from BC-201, was around 50%.

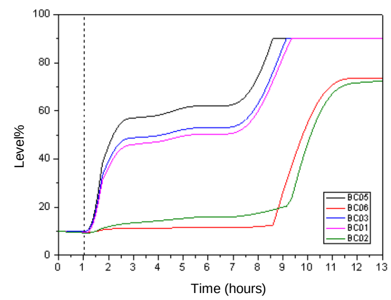
Figure 32 shows the amount of water accumulated inside the refinery during the event. It is important to emphasize that the basin (T-8C-2E) and the bauxite and coal areas exceeded the maximum limit, and this excess rain water can remain in the areas in interior of the refinery or be directed to the old channel. According to the company, the old channel was used to dispose of excess rain water.
Figure 33a shows the comparison between the outflow generated by the refinery and the one generated by rainwater, where you can see the huge difference between the two flows; that is, the ETEIs were at full capacity

to treat basically rain water. Figure 34 shows the percentage of the operational capacity of ETEI during the event.

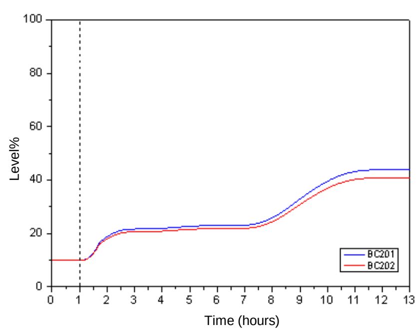
Figure 33b shows the comparison between the actual and the predicted by the model of the water accumulated during the rainfall, where is possible to realize the good adhesion between them. From the analysis of this figure and the description of the event occurred between February 16 and 17, 2018, it was concluded that the model generated in Aspen™ can be used for assessment of other scenarios.



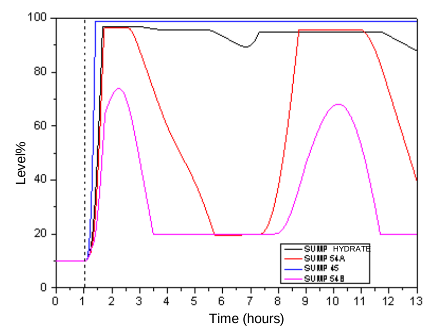
(a)



(b)



(c)



(d)

Figure 31 - Basins' level during the event of February 16 and 17, 2018, considering the PFD of February 2018.

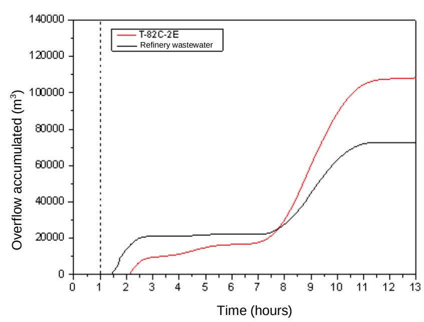
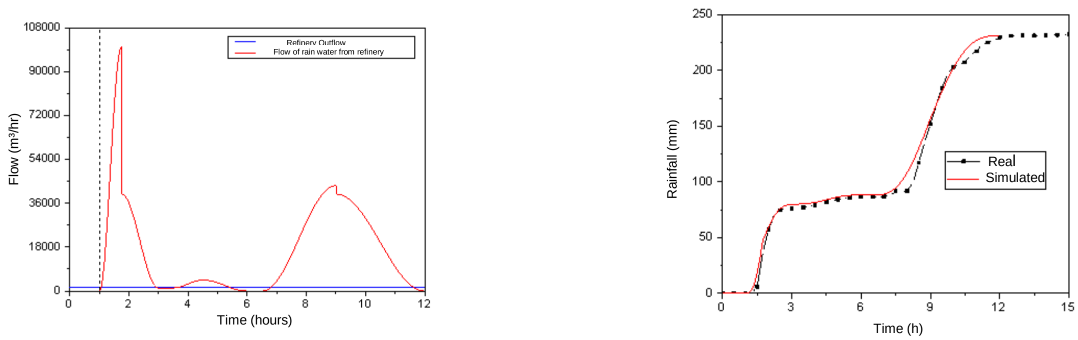


Figure 32 - Water accumulated inside Alunorte during the event of February 16 and 17, 2018, considering the PFD of February 2018.



(a) (b)

Figure 33 - Outflow from the refinery, water flow generated by rain during the event of February 16 and 17, 2018 and validation of the rain profile, considering the PFD of February 2018.

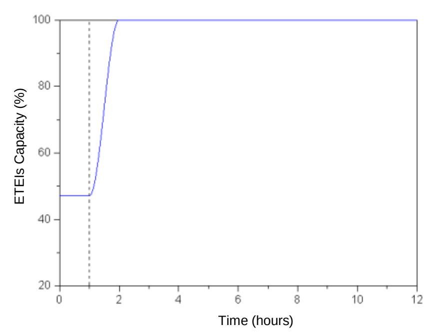
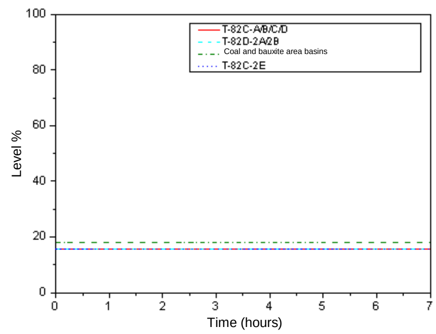


Figure 34 - ETEI operational capacity during the event of February 16 and 17, 2018, considering the PFD of February 2018.

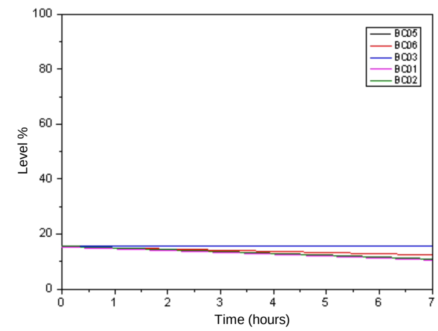
Scenario 2 - Refinery initially generating 1,480 m^3/h and then 2,100 m^3/h wastewater, without rain and PFD of February 2018;

The evaluation of this scenario aimed to show the behavior of ETEI DRS1, and DRS2 basin levels, considering the refinery generating 1,480 and 2,100 m^3/h wastewater, respectively. Otherwise, the objective was to show the impact of the outflow generated by the refinery on the ETEI operation. The evaluation also serves to show the percentage commitment of ETEI's storage/treatment capacity.

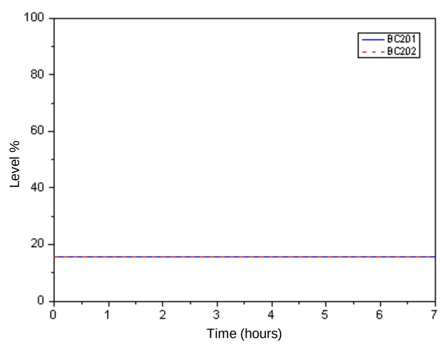
According to figure 35, only the DRS1 basin level, as shown in Figure 35b, shows little variation (for less), since without the occurrence of rain, the ETEIs also operate treating their wastewater (in this scenario, DRS2 basins' wastewater were not being treated).



(a)



(b)



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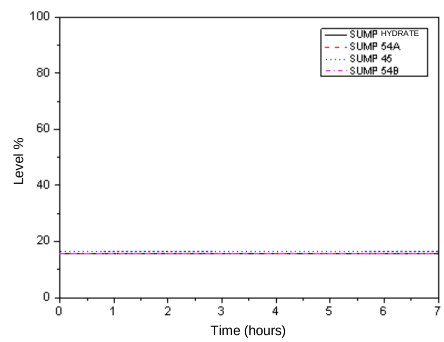
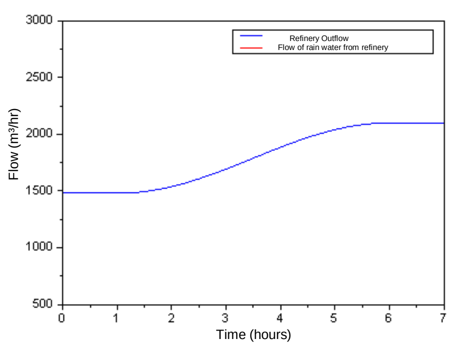


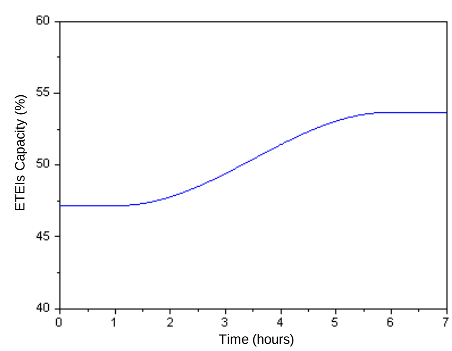
(d)

Figure 35 - Level of the basins and sumps for the increase in outflow, considering the PFD of February 2018.

Figure 36a shows an increase in outflow generated by the refinery, while figure 36b shows the percentage commitment of use of ETEI.



(a)



(b)

Figure 36 - Outflow and rainwater flow and percentage of use of ETEI, considering the PFD of February 2018.

Based in figures 35 and 36, it is observed that the ETEIs have a handling capacity far superior to the outflow of wastewater generated at the refinery. For the conditions of the refinery generating 1,480 and 2,100 m^3/h, and also treating waste water from DRS1 basins, the percentage of use of ETEI is committed between 40 and 55%, respectively.

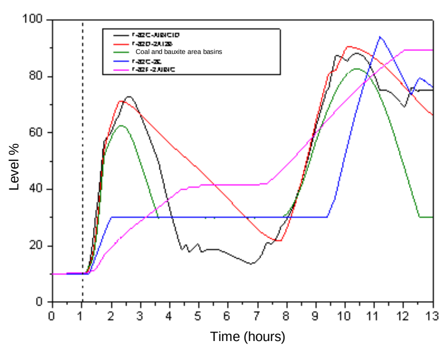
These results show that reducing the operational capacity of Alunorte has little or no influence on the treatment of wastewater, as the limiting factor of ETEI is the amount of rainfall; that is, for both outflows assessed, without the modifications that are being carried out, if there is a rain such as the one on February 16 and 17, 2018, the production reduction of 50% imposed does not represent any increase in operational safety.

Scenario 3 - Refinery generating 2,100 m3/h wastewater, considering the February 2018 rain, new basins and sumps catchment areas, new pumping capacity and PFD of December 2018

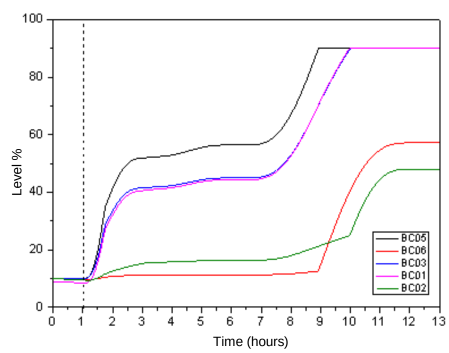
This scenario had as objective to evaluate the behavior of the level of basins and *sumps,* considering new pumping capacity, the change in basins and sumps catchment area (Table 13) and the PFD of December 2018.

As shown in Figure 37a, no area 82 basin reached maximum level, the same observation also holds for the *sumps,* as shown in Figure 37d; noting that the constant level corresponds to 90% of total capacity, the wastewater is being directed by gravity or by pumping.

This result indicates that the reduction of the catchment area of the *sumps,* the construction of the new basin and the new pumping capacity are sufficient to mitigate the effect of rainfall, avoiding any type of flooding within the refinery.



(a)



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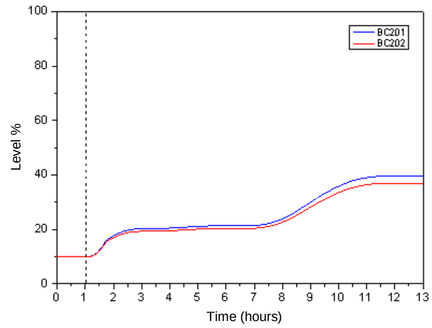

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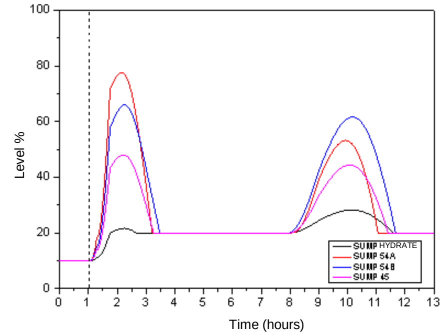


(d)

Figure 37 - Basins' level considering the event of February 16 and 17, 2018, new catchment area, new pumping capacity and the PFD of December 2018.

It is interesting to note in Figure 37d that the level behavior accompanies the rainfall (Figure 24); when the rain is more intense, the sumps level reaches the maximum value, decreasing when the rain decreases.

Figure 37b shows that there was no escape of wastewater from DRS1, since the level of basins BC-02 and BC06, which are the last ones in the sequence of wastewater transport (see Figure 17), was around 60%. Once again, noting that constant level is equal to 90%, which means that the wastewater is being transferred or poured into a nearby basin. Figure 37 c shows that the DRS2 basin level did not reach even 40%

The result obtained for this scenario shows that in December 2018, with the modifications made in the catchment area, in pumping and with the construction of the new basin, Alunorte's industrial wastewater management system will bear an extreme rain as the one that occurred between February 16 and 17, 2018.

Refinery generating 2,100 m^3/h wastewater, considering average rainfall of 22.77 and 12.86 mm/h, for 12 and 24 hours, respectively, new basins and sumps catchment areas, new pumping capacity and PFD of December 2018;

This scenario considered 273.24 mm rainfall in 12 hours and 308.64 mm in 24 hours, which represent, according to table 16, two rains with return period of 10,000 and 5,000 years old, respectively. In addition, it is important to highlight that these are greater rains than the rainfall that occurred between February 16 and 17, 2018.

The evaluation of this scenario also serves to compare the difference in behavior of levels caused by the rainfall profile.

Figure 38 shows the rain profile of 22.77 mm/h during 12 hours and the amount of water accumulated during rainfall. Figure 39 shows the flows generated by rain and the refinery, and the flow pumped to the new basin (82F). In addition, the simulation time is 13 hours, because rainfall only starts after the time of 1 hour.

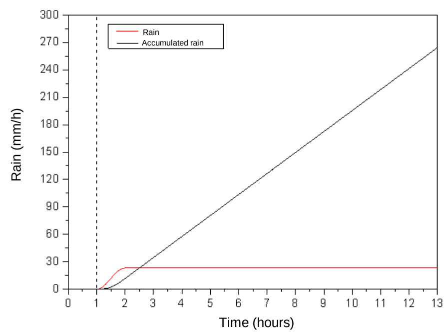


Figure 38 - Rain profile of 22.77 mm/h for 12 hours and accumulated water.

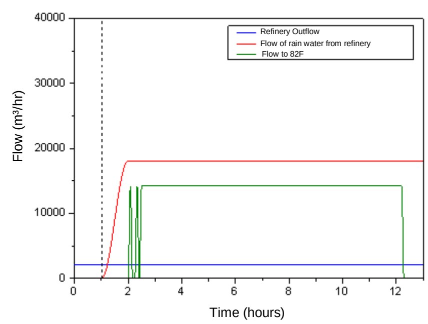


Figure 39 - Outflow generated by the refinery and the rain of 22.77 mm/h for 12 hours.

According to Figure 39, due to the difference between the flows, once again, it is possible to notice that the highest percentage of ETEI processing is used to treat the wastewater generated by the rain.

According to the Figure 40a, no area 82 basin reaches maximum level during the 12 hours of rainfall; a result that is only achieved because the new basin (T-82F-2/A/B/C) functions as a lung, buffering the effect of rainfall on the other basins, in addition to the changes in the catchment area and pumping. Similarly, Figure 40 d shows that no *sump* reached the maximum level.

Figure 37b shows that there was no escape of wastewater from DRS1, since the level of basins BC-02 and BC06, which are the last ones in the sequence of wastewater transport (see Figure 17), was between 70% and 80%. Figure 37 c shows that the DRS2 basin level reached a little above 40%.

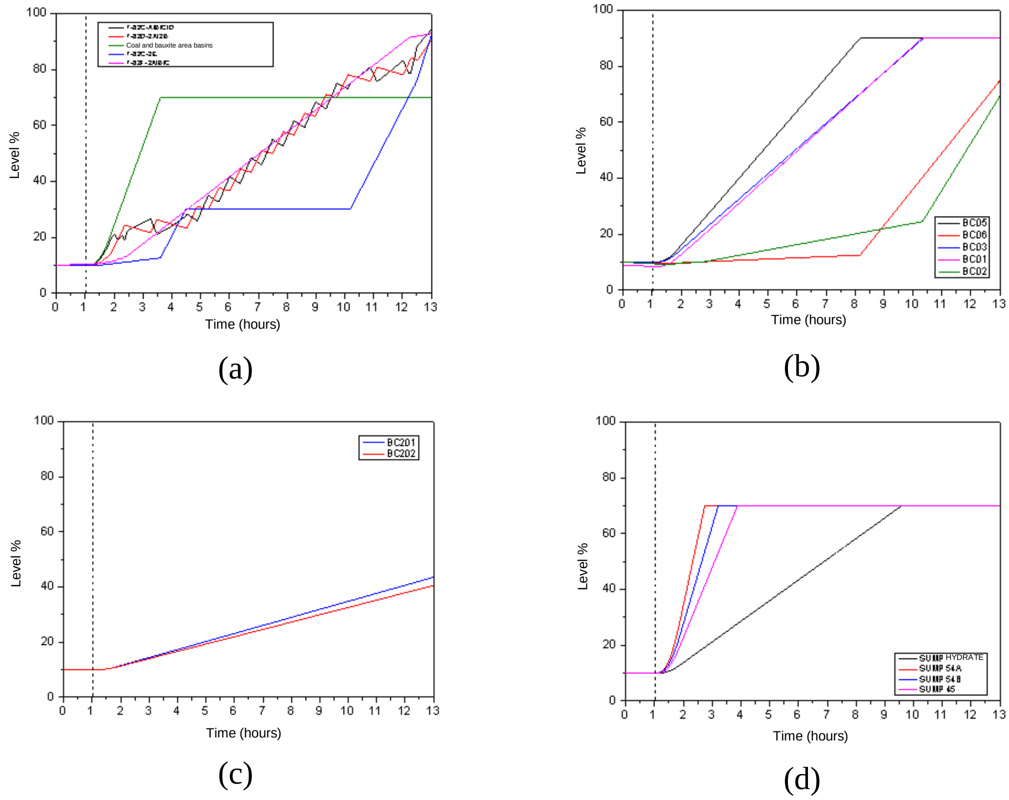


Figure 40 - Basins' level considering a rainfall of 22.77 mm/h for 12 hours, new catchment area, new pumping capacity and the PFD of December 2018.

Comparing figures 37 and 40, it is possible to observe the effect of "downpour" caused by the rain that occurred on February 16 and 17, 2018, when the level of basins and *sumps,* especially, increased rapidly.

Figure 41 shows the behavior of the level to basins and *sumps,* considering a rain of 12.86 mm/h for 12 hours, where it is observed that, despite the greater amount of water that rains, as expected, the basin level increases more slowly.

No area 82 basin reaches maximum level (Figure 41); and the same observation goes for sumps (Figure 41d) and basins of the DRSs (figures 41b and 41c).

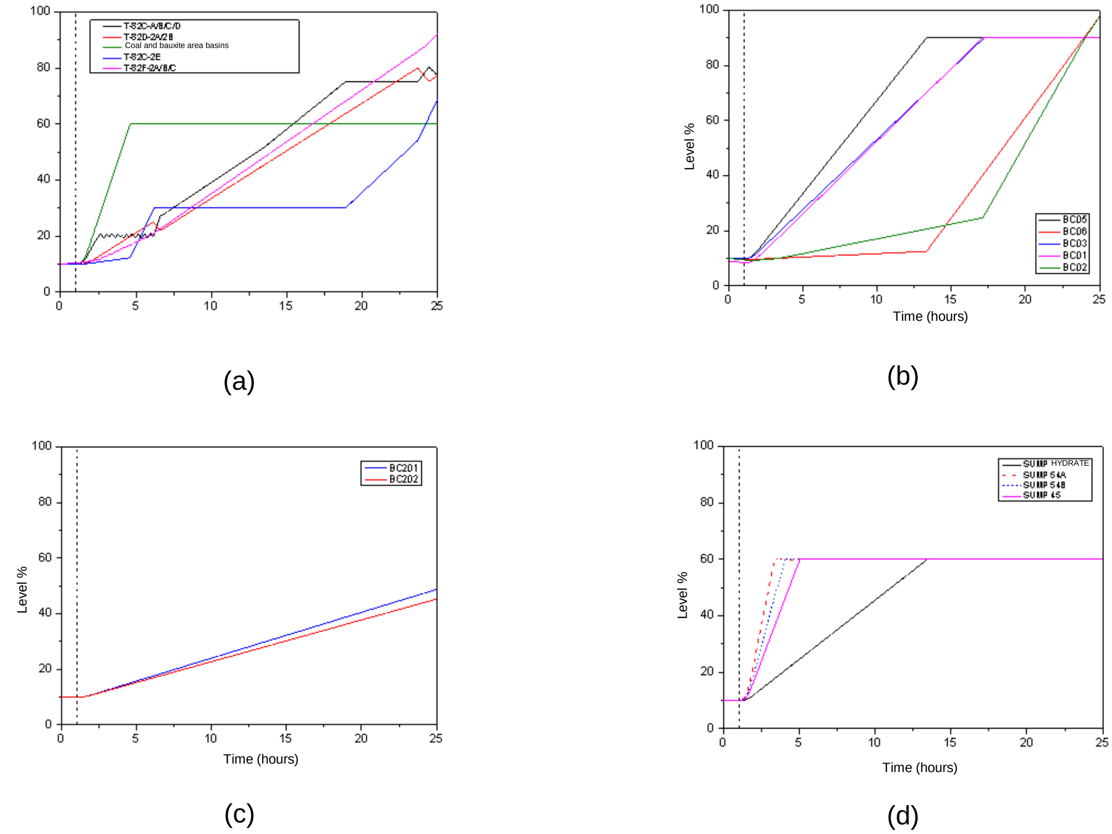


Figure 41 - Basins' level considering a rainfall of 12.86 mm/h for 24 hours, new catchment area, new pumping capacity and the PFD of December 2018.

The results presented in figures 40 and 41 indicate that the modifications implemented (storage, catchment area, pumping capacity) make Alunorte's wastewater management system able to face rains with return periods of 10,000 and 5,000 years, with duration of 12 and 24 hours, respectively, with no risk of escape of wastewater in the internal areas of the company.

Scenario 5 - Refinery generating 2,100 m^3/h wastewater, considering average rainfall of 22.77 and 12.86 mm/h, for 12 and 24 hours, respectively, new basins and sumps catchment areas, new pumping capacity and PFD of May 2019;

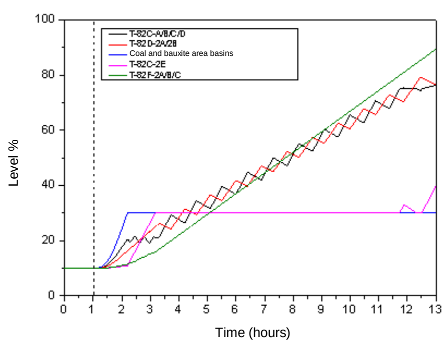
This scenario considered the PFD of May 2019, which includes a new ETEI, which should improve even more the performance of the system. However, the goal was to observe the effect of the construction of a new ETEI on Alunorte's wastewater management capacity, in extreme rain condition.

Figure 42 shows the results for rain with return of 10,000 years (22.77 mm/h, during 12 hours), where you can see that no area 82 basin reached maximum level, as expected, and the same was observed for the *sumps*. Comparing figures and 40b, 42a we can see that the level of the new basin (T-82F-2/A/B/C), of basins T-82C/2A/B/C/D and T-82D/2A/2B were lower for the situation in May 2019, exactly because of the new ETEI; in other words, less accumulation of wastewater in these basins.

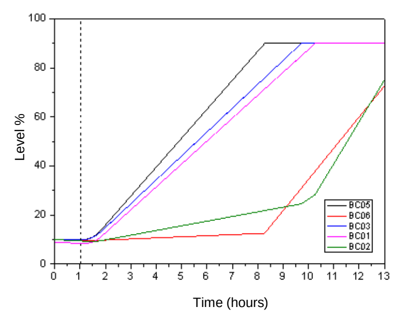
The results for the DRSs (figures 42b and 42c) are similar to the previous scenario (figure 40b and 40c), when it is observed that no basin reaches maximum level.

Figure 43 shows the results for rain with return of 5,000 years (12.86 mm/h over 12 hours), where you can see results similar to those observed for rain with return period of 10,000 years over 12 hours: there is no escape of wastewater from Alunorte’s inner area.

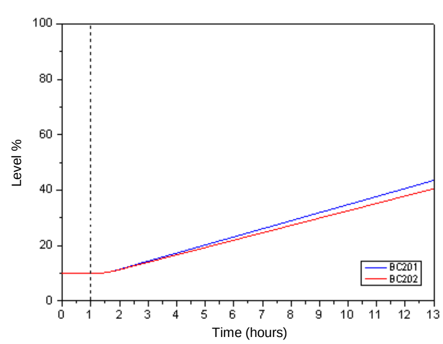
Objectively, we can affirm that in May 2019, the system is able to cope with a rainfall with return periods of 10,000 and 5,000 years for 12 and 24 hours, respectively.



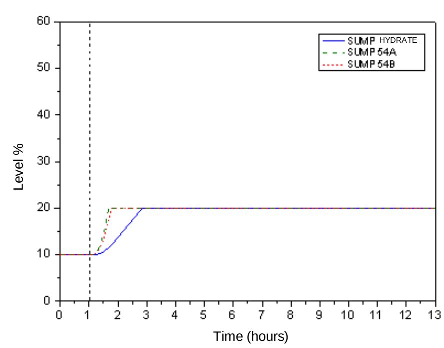
(a)



(b)



(c)



(d)

Figure 42 - Basins' level considering a rainfall of 22.77 mm/h for 12 hours, new catchment area, new pumping capacity and the PFD of May 2019.

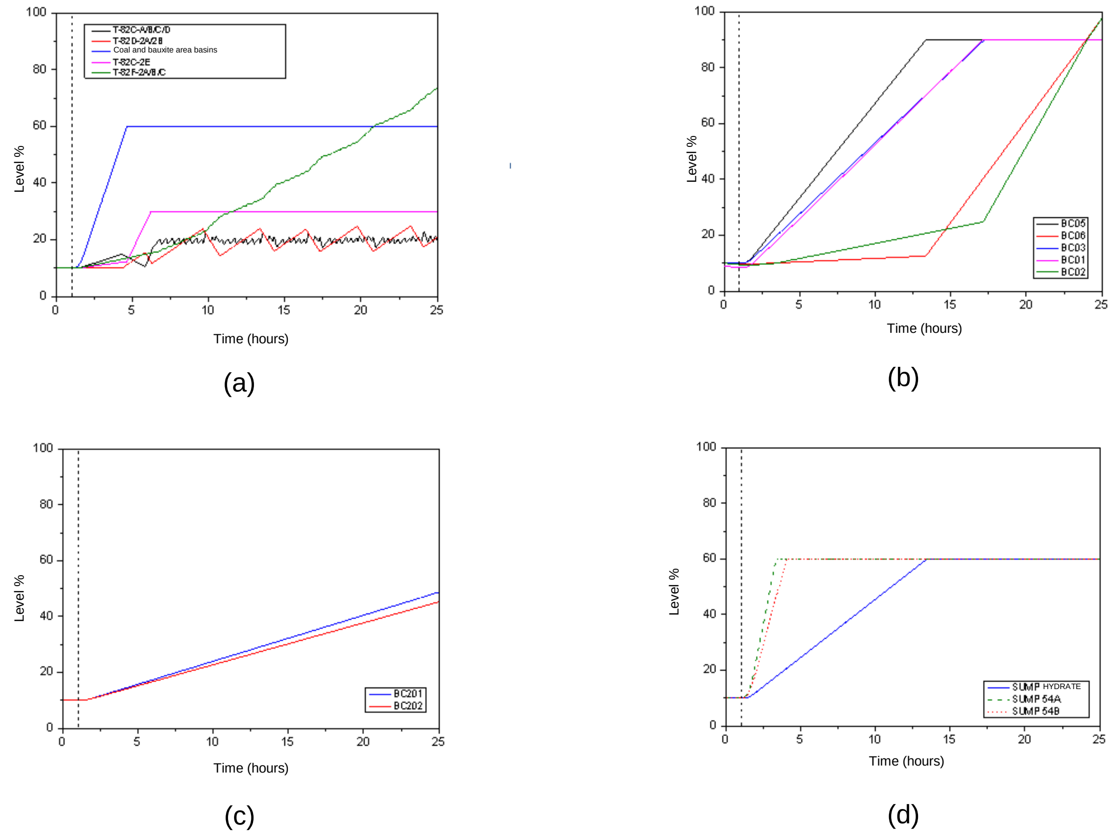


Figure 43 - Basins' level considering a rainfall of 12.86 mm/h for 24 hours, new catchment area, new pumping capacity and the PFD of May 2019.

9. CONCLUSIONS

A rigorous mathematical model in transient regime for Alunorte's wastewater circuit was developed, in order to evaluate different scenarios involving rainfall, operational procedures, and wastewater storage, pumping and processing capacity.

The model can reproduce the events between February 16 and 17, 2018, as described by Alunorte's team of engineers and verified by document analysis and field inspections during the month of October 2018, so that it provides enough precision to answer questions regarding different scenarios involving: i) wastewater storage, pumping and processing capacity; II) alumina production levels; III) rainfall.

According to the results of the simulations:

- The level DRS 1 and DRS2 basins did not reach the maximum value during the rain occurred on February 16 and 17, 2018;
- On February 17, 2018, the old channel was used for disposal of excess rain water collected in the area of the refinery, a suitable decision under the circumstances, to avoid a potential environmental risk;
- The results of the simulations show that the reduction in the level of Alunorte's alumina production does not represent an increase in operational safety, since the processing capacity of the ETEI is significantly larger than the outflow generated by the refinery, which has low sensitivity to variation in the level of production.
- The generation of wastewater from Alunorte's refinery represents between 10 and 20% of the ETEI treatment capacity;
- The improvements implemented or being implemented at Alunorte, ensure that wastewater management system supports an event like the one on February 16 and 17, 2018, without requiring the use of the old channel to dispose of excess rain water;
- The improvements implemented or being implemented at Alunorte, ensure that wastewater management system supports a rain event with return period equal to 10,000 and 5,000 years, with duration of 12 and 24 hours, respectively, without requiring the use of the old channel for disposal of excess rain water;
- The improvements implemented or being implemented at Alunorte meet NBR 13028 of 2017, which states that the overflow systems of geotechnical structures with high Potential Damage must be set for a return period of 1,000 years or more, during the operational period of the structure; and 10,000 years or above for the period of structure closure.

In view of the foregoing, the experts conclude:

- Currently, from the point of view of wastewater management, it is safe for Alunorte to produce at nominal fee of 6.3 million metric tons of alumina a year.
- With the improvement projects that are being implemented, Alunorte is prepared for possible future changes in climate, which could lead to more frequent extreme rain events, as of December 2018.

10. BIBLIOGRAPHICAL REFERENCES

Associação Brasileira de Normas Técnicas, NBR 13028: 2017

Associação Brasileira de Normas Técnicas, NBR 13029: 2017

Alunorte's Institutional presentation, March 2018a.

Alunorte's Institutional presentation, March 2018b.

Conklin, H. L. Water Requirements of the Aluminum Industry. United States Government Printing Office, Washington, 1956.

Enviro-Tec do Brasil Consultoria e Tecnologia Ambiental Ltda, Technical Report, 2018.

Farias, C. P. C. Atlas Pluviométrico do Brasil: Equações Intensidade-Duração-Frequência, Barcarena, 2018.

Habashi, f. (2005). A short history of hydrometallurgy. Hydrometallurgy.

https://bacana.news/e-assustador-os-impactos-economicos-que-paralisacao-da-hydro-causara-entenda-o-caso/

Hind, R. A. (1999). "The surface chemistry of Bayer process solids: a review", Colloids and surfaces a: Physicochemical and engineering aspects.

Normative Instruction SEMAS n. 02/2018

Federal Law n. 12.334, September 20, 2017.

Alunorte's Sustainability Report 2010-2011, 2011.

CONAMA Resolution n. 430, May 13, 2011.

Santana, F. S. M. Balanço Material para Maximização do Desempenho de Recuperação de Alumina no Processo Bayer. Dissertation (Master in Chemical Engineering) – UFCG. Campina Grande-PB, p. 16. 2012.

Santos, W. **Caracterização e análise de pisos intertravados utilizando a lama vermelha.** Thesis (Ph. D. in chemical engineering) - Department of Chemical Engineering, Universidade Federal de Campina Grande, Campina Grande, p. 93.2012.

Instituto Nacional de Meteorologia (INMET). Available at: <http://www.inmet.gov.br/portal/>. Access on November 06, 2018.

Souza, R. O. R. S., Scaramussa, P. H. M., Amaral, M. A. C. M., Pereira Neto, J. A., Pantoja, A. V. e Sadeck, L. W. R. Equações de chuvas intensas para o Estado do Pará, Revista Brasileira de Engenharia Agrícola e Ambiental, v.16, n.9, 2012.

Torres, A. A. O. Modelagem do Processo Bayer utilizando o software comercial Aspen Plus. Dissertation (Master in Chemical Engineering) – UNICAMP. Campinas-SP, p. 27. 2001.

http://seirh.semas.pa.gov.br:81/SISMET/faces/climatologico/ Access on 11/5/2018 at 16:18

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