MAPPING OF WATER CIRCULATIONS AND MASS BALANCES AT BILLERUD PIETARSAARI PAPER MILL

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Water Technology, Master's thesis

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ABSTRACT

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In this thesis, water circulations and water balances of Billerud Pietarsaari paper mill are mapped. Consumers' environmental awareness has created a new requirement for the assessment of the environmental impacts of products and services, and how they should be communicated to stakeholders. For this reason, it is important that the production process is regularly mapped to offer up-to-date data for assessment of environmental impacts.

Mapping water circulations and water balances aims to locate the water consumption of different unit processes. The mapping also serves as a groundwork for the life cycle assessment tool developed by Billerud, which collects data related to the factory's production process. Based on the conclusions of the survey, the available data is known and suggestions for further research and solutions to decrease water consumption can be made.

The mapping of water circulations and mass balances found that sufficient water flow related data is available for life cycle assessment. Closer examination of water streams was able to identify development targets that can reduce the plant's water consumption and the amount of wastewater led to wastewater treatment plant. Monitoring of water consumption could be facilitated through, for example, a simulation model or a visual tool, or by investing to instruments, which allow to collect data from more data points.

TIIVISTELMÄ

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Vesikiertojen ja vesitaseiden kartoitus Billerud Pietarsaaren paperitehtaalla

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50 sivua, 12 kuvaa, 9 taulukkoa ja 0 liitettä

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Avainsanat: paperikone, vesikierto, vesitase

Tässä diplomityössä kartoitetaan Billerud Pietarsaaren paperitehtaan vesikiertoja ja vesitasetta. Kuluttajien ympäristötietoisuus on luonut uuden vaatimuksen tuotteiden ja palveluiden ympäristövaikutusten arvioinnille ja kuinka niistä kommunikoidaan sidosryhmille. Tämän vuoksi on tärkeää, että tuotantoprosessia kartoitetaan säännöllisesti, jotta käytettävänä on ajantasaista dataa ympäristövaikutusten arviointia varten.

Vesikiertojen ja vesitaseiden kartoittamisella pyritään paikantamaan eri osaprosessien vedenkulutusta. Kartoitus toimii myös pohjatyönä Billerudin kehittämälle elinkaarilaskennan työkalulle, johon kerätään dataa tehtaan tuotantoprosessiin liittyen. Kartoituksessa tehtyjen johtopäätöksien perusteella tiedossa on käytettävissä olevan datan määrä ja sen perusteella voidaan tehdä ehdotuksia tarvittavista jatkotutkimuksista sekä mahdollisista muista vedenkulutukseen liittyvistä toimista.

Vesikiertojen ja vesitaseiden kartoituksessa havaittiin, että käytössä on riittävästi vesivirtauksiin liittyvää dataa elinkaarilaskentaa varten. Vesivirtauksien lähemmällä tarkastelulla pystyttiin havaitsemaan kehityskohteita, jotka voivat vähentää tehtaan vedenkulutusta ja jäteveden puhdistamolle johdettavan veden määrää. Vedenkulutuksen seurantaa voitaisiin helpottaa esimerkiksi prosessisimulaation tai visuaalisen työkalun avulla, sekä instrumenttihankinnoilla, jotka mahdollistaisivat datan keräämisen useammista pisteistä.

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Vaasa, 31.11.2022

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ABBREVIATIONS

ADt	Air Dry Ton
AOX	Adsorbable Organic Halides
BAT	Best Available Techniques
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
HC	High Consistency
LCA	Life Cycle Assessment
TSS	Total Suspended Solids

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1 Introduction

Paper manufacturers are continuously trying to reduce water usage for keeping up with the competition in the industry, even though paper industry has already successfully decreased fresh water consumption over last decades. Most of the water is consumed in the dilution and transportation of raw material, which is compensated with reusing water within the process. Reusage of water can be still challenging for paper quality or affect the runnability of paper machine. (Ordóñez, Hermosilla, de la Fuente & Blanco 2009)

Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board (2015) offers useful data for paper manufacturers for integrated pollution prevention and control according to Industrial Emissions Directive 2010/75/EU. They have reported that annual average of fresh water inflow for a non-integrated speciality paper mill is approximately 13.4 m^3/ADt. This water consumption is mainly constituting from fiber material dilution, showering of paper machine equipment, and cooling or sealing of process systems. Wastewater outflow is approximately 13.0 m^3/ADt and the most common pollutant is dependent on the type of paper manufactured. Water consumption is controlled, and wastewater pollution should be minimized to decrease the harmful environmental impacts of the paper manufacturing process.

Comprehensive environmental impacts of product or process can be evaluated with life cycle assessment (LCA). If there is a desire to take a closer look at water-related environmental effects, the water footprint of a product can be assessed. The water footprint of a product tells how much and what type of water is used during the manufacturing process and supply chain of the product. Assessment is divided to green, blue, and grey water footprints depending on the origin of water, in which green water is originated from rain, blue water from irrigation and grey water implies how much water is polluted. Product water footprint is an important tool to describe embedded water, which might not be visible in the product itself. The typical unit for a product water footprint is m^3/ton. This information can be shared as a part of traditional LCA. (Hoekstra, Chapagain, Aldaya & Mekonnen 2011, 46–47, 94)

1.1 Aim of the study

This master’s thesis has been carried out at Billerud Pietarsaari paper mill. Pietarsaari mill has one paper machine (PM1), which produces 200 000 tons of sack and kraft paper per year. (Billerud n.d.) As a manufacturer of sustainable packaging materials, Billerud wants to upgrade environmental performance of the production process and provide up-to-date environmental data for the customers. For this reason, Billerud is developing own third party approved LCA tool for packaging materials. Own tool provides an advantage compared to traditional life cycle assessment, which is very time consuming, because the assessment requires high amount of data. Using own tool allows efficient assessment of the products, since the tool encloses database including data from Billerud’s production. The tool aims at improving environmental communication and sustainability reporting by providing customers more information related to environmental impacts of the product. (Billerud 2022)

The study aims at mapping the water circulations and mass balances at PM1. Mapping of water circulations and mass balances will work as preliminary survey and compile data for LCA tool. These findings can be connected to specific product groups and therefore recognize from which operations fresh water footprint of the different product groups are consisting of.

1.2 Structure of the study

This study includes a literature part and an applied part. The literature part is firstly focusing on giving a brief introduction to paper manufacturing process and different water fractions used at paper mill. In addition, the literature part provides a general view to paper mill short, long, and tertiary water circulations and a concept of mass balance.

The literature part is followed by the applied part, which covers more specific presentation of water fractions and water circulations at Billerud Pietarsaari PM1. Mapping of water circulations includes collection of flow rate data, which is later used to determine mass balances for PM1 and vacuum system. Results found are used to evaluate obtainable data for LCA tool and to locate the most water consuming operations, which are increasing water consumption and product water footprint. Mapping of water circulations and mass balances lays the groundwork for planning actions for water use reduction.

LITERATURE PART

2 Paper manufacturing process

According to Ek, Gellerstedt and Henriksson (2009a, 6–7) papermaking can be divided into stock preparation and paper machine. These operations include preparation of raw material for the manufacturing process and formation of the paper. This section describes the basics of the paper manufacturing process.

2.1 Stock preparation

Pulp for the paper manufacturing process can be received straight from the pulp mill, if the paper mill is located close enough to pulp mill to pump the pulp through a pipe. Stock can also be prepared from dried pulp bales by slushing. Bales are broken down in a pulper with addition of water and mechanical stress created by a rotor. The consistency of the fiber slurry formed within this operation is typically 4–8% depending on the type of pulping process. The texture of the slurry should be even. (Paulapuro 2008, 78–82) After slushing the fiber slurry can be defibrated or refined to optimize the structure of the fibers to meet the demands set for the strength and surface properties of the paper. The consistency of the fiber slurry in this phase is approximately 4–5%. During defibration and refining, coarse filling bars are grinding the fibers, which breaks down the surface of the fiber and cuts them into shorter pieces. For example, the density of the paper increments as a result of refining. (Paulapuro 2008, 88, 94–95)

Fiber slurry is diluted and screened during stock preparation to ensure the right consistency and purity of stock for further operations. The stock is treated with additives such as biocides, sizing agents and retention aids to either enhance the manufacturing process or to provide desired properties for finished paper. Therefore, the chemical, physical and biological characteristics of the stock are adjusted to the final form within this phase. Before treated slurry is pumped to paper machine, fiber slurry is stored in machine chest in consistency of 2.6–2.8%. (Bajpai 2018, 65–68, 77)

2.2 Paper machine

Fiber slurry enters the paper machine via headbox. Diluted stock is distributed on continuously rolling wire screen forming a web. The consistency of fiber slurry is only 0.3–0.6% while arriving to the headbox, and removal of water begins immediately between the wire threads with the help of suction and pressure created by the rolls. Wire section of paper machine increases the consistency of web into 18–23%. Water removal continues at press section, where the web is directed through nips pressing even more water away from the web providing consistency of 35–55%. (Bajpai 2018, 95–97) Drying section finalizes the paper drying process so after drying section paper has reached the desired consistency. The drying section includes multiple heated cylinders, and the high temperature of the surface makes water evaporate from the web. Typical moisture content for finished paper is below 10%. (Calvo & Domingo 2017) Simplified schematic of paper machine water removal process is presented in Figure 1.

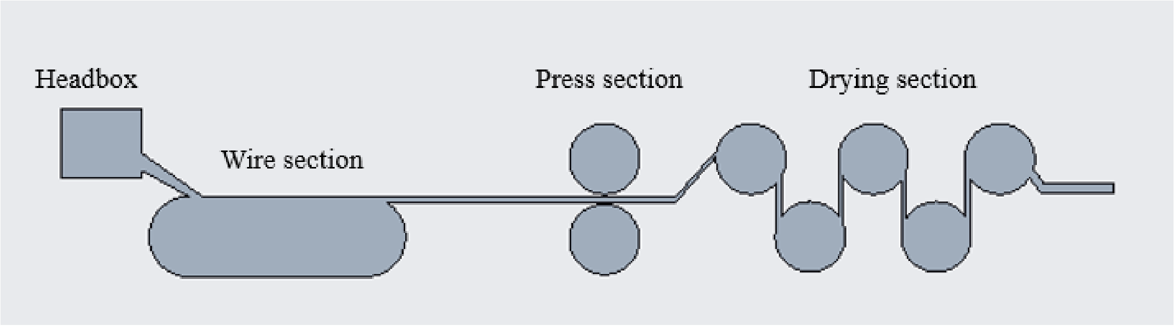

Figure 1. Simplified paper machine water removal process (Modified from Li, Ramaswamy & Bjegovic 2003)

2.3 Finishing operations

Surface of paper might still need modification, even though the final consistency has been reached. The main goal of modification is to improve the surface properties of paper for further processing, like printing, which requires enhanced absorption and roughness to make the printing successful. For example, calendering process is a common finishing operation, in which the paper is compressed between calender nips. As a result of the pressure, the thickness of paper decreases, and surface properties are changing. (Rautiainen 2010, 14–15, 18)

When paper produced at paper machine has achieved the aimed properties, it is reeled to large rolls named parent rolls. Parent roll is adjusted to meet the customer demands via winding process, in which the parent roll is winded into smaller diameter and width according to customer requirements. As a part of the winding process, the quality of the paper can be monitored since the customer will rewind the roll as well. For instance, edges of the roll are cut with sharp blades to provide clean roll edges and smooth runnability for the next steps of processing. These shipping rolls are typically wrapped and labelled before delivery to cover reels during transportation and ensure the identification of reels. (Rautiainen 2010, 176–178, 286–287)

3 Paper mill water fractions

Fresh water consumption in paper industry has been massive, since the process itself is water intensive and water is lost via evaporation as well. Nowadays approximately 92–95% of water can be reused after suitable water treatment, which has improved the reputation of paper and pulp industry. Quality of fresh water is not high enough for paper production, so it is treated in different ways at paper mill to meet the quality specifications for different operations. (Blanco, Hermosilla & Negro 2015, 213–237)

3.1 Mechanically purified water

Fresh water cannot be used for all the applications at paper mill because of high concentration of solids. Anyhow, fresh water can be treated with mechanical methods to improve the quality. When water from close locating fresh water bodies is pumped to mill, the number of solid particles in water can be decreased with filters and screens. Typically, the first step of mechanical purification is performed with screens having a hole diameter of 15–20 mm. Purification is completed with screening bars with spacing of 10–25 mm. Even though screens and filters are not able to clarify water completely, parameters, such as colour and concentration of manganese or iron, are controlled. Since mechanical purification does not remove water colour caused by humus, it is usually used for manufacturing unbleached products or when high purity is not needed. (Dahl 2008, 56–60)

According to Holik (2006, 208–218) fresh water does not meet the requirements for most of paper mills, as the end use of the paper can set tight demands for the manufacturing process. There are still operations, such as sealing vacuum pumps and other equipment using water, which can utilize less purified water pumped from fresh water body. In addition, cooling water used for collecting waste heat from the process and reusing it for heating does not require high purity either.

3.2 Chemically purified water

Fresh water can be chemically treated into high quality chemically purified water by reducing the content of organic material and metals. As metals and organic material are treated with very different mechanisms, chemical purification process is usually a set of different phases. This usually means combining chemical oxidation and chemical precipitation. With addition of chemicals, such as permanganate, metal ions are oxidized, and formation of flocs is enhanced with coagulant. Wastewater is continuously mixed during this phase. Most of the formed flocs are removed by clarification, in which heavier flocs are settling at the bottom of the clarifier. Remaining flocs are eliminated in filtration, where water is draining through the filter bed. Purified water can be disinfected with chemicals like hypochlorite or chlorine before locating to storage. (Dahl 2008, 61–66) Simplified process for chemical purification of fresh water is presented in Figure 2.

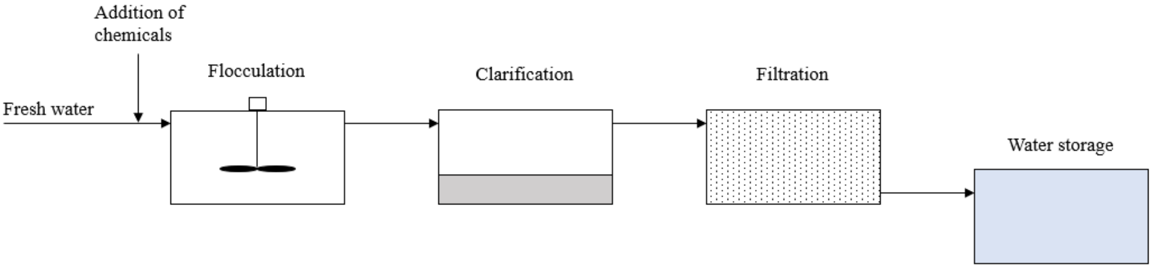

Figure 2. Chemical purification of fresh water. (Modified from Dahl 2008, 61)

3.3 White water

Water removed from fiber slurry while producing paper is called white water, because it contains fine cellulose fibers making the colour of water white. White water is recirculated back to paper machine to decrease water usage at paper mill. As white water includes raw material percolated from paper machine, recirculation allows to utilize fibers and additives in white water again. White water is also used for diluting broke material formed at paper machine, which is used to manufacture new material as well. (Khanbaghi, Malhame & Perrier 2002)

Recirculating water at paper mill decreases the fresh water consumption and process wastewater load. On the other hand, closed water circulations make paper manufacturing process becomes more complicated and circulating solids and other substances can accumulate causing problems, such as corrosion or clogging, with process equipment or decrease microbiological purity of water. Water recirculation is generally applicable for all paper mills, but build-up of colloidal material and dissolved organics or inorganics can limit the possibilities to recirculate water in some applications, if paper quality requirements cannot be met with recirculated water. (Suhr, Klein, Kourti, Gonzalo, Santonja, Roudier & Sancho 2015)

3.4 Process wastewater

Producing one tonne of paper generates approximately 60 m^3 of process wastewater. Organic matter ends up to wastewater via rejects around the process. For example, almost 50% of process wastewater generated can be composed of white water including cellulose fiber containing rejects from screening and wire section, as well as additives used in manufacturing process. Paper mill process wastewater is typically treated with primary clarification removing suspended solids and followed by biological treatment degrading organic matter. Purification can be completed with tertiary treatment, such as membrane filtration, if there are characteristics like residual chemical oxygen demand (COD) or colour, which should be removed. (Thompson, Swain, Kay & Forster 2001)

Emission limits and environmental monitoring is country specific, why emission data from different countries includes varying information. Typical composition of paper mill wastewater contains approximately 800 mg/L total suspended solids (TSS), 1600 mg/L biological oxygen demand (BOD) and 5020 mg/L COD. Content of total nitrogen is approximately 11 mg/L and total phosphorus 0.6 mg/L. Clarification can remove 80–90% of TSS and biological wastewater treatment methods can decrease BOD content > 80% and COD content > 70%. Integrated wastewater treatment methods have been finding out to remove > 50% of total nitrogen and > 90% of total phosphorus. (Pokhrel & Viraraghavan 2004)

Council Directive 2010/75/EU (2014) has published BAT conclusions for the production of pulp, paper and board. Emission limit values stated by BAT are setting the limits for environmental permit conditions and environmental monitoring requirements. For example, for a non-integrated speciality paper mill, BAT has established emission levels presented in Table 1 for process wastewater.

Table 1. BAT emission limits for a non-integrated speciality paper mill (Council Directive 2010/75/EU, 2014)

Parameter	**Yearly average [kg/ADt]**
COD	0.3–5
TSS	0.10–1
Total nitrogen	0.015–0.4
Total phosphorus	0.002–0.04
Adsorbable Organic Halides (AOX)	0.05

These BAT emission limits are applied for PM1 as a part of supervision performed according to environmental permit.

4 Paper mill water circulations

According to Bajpai (2018, 314) paper mill water circulations can be divided to short circulation, long circulation, and tertiary circulation. This section introduces basic operations of conventional water circulations at paper mill.

4.1 Short circulation

Thick stock is diluted and mixed with white water at wire pit. Short circulation starts, when diluted fiber slurry exits machine chest. Machine screens are placed in early phase of short circulation to remove hard impurities, such as sticks, which could damage paper machine. Accept and reject flows are recirculated until the concentration of fibers in reject is such low, that it can be led out the system. Machine screening is typically followed by centrifugal screening, in which impurities with higher density than diluted stock are removed in cyclones based on centrifugal forces. Great number of cyclones are located parallel to handle flow despite the small diameter of cyclones. Diluted stock enters cyclones tangentially and reject flow exits from the bottom. Accept passes the cyclone from the top of the cyclone. Centrifugal screening can compose of even six stages to reach fiber level of reject low enough. (Ek et al. 2009b, 137–146)

Air bubbles needs to be removed from diluted stock before headbox, because they can for example harm the proper working of dewatering at wire section. Deaeration means eliminating air bubbles from the diluted stock before is pumped to headbox. Diluted stock is spread out to a vacuum tank, where vacuum system separates air bubbles and removes them from the system. When air bubbles are removed, diluted stock can be pumped to headbox with high pressure without weaken quality of headbox jet. (Ek et al. 2009b, 137–146) Diagram of conventional short circulation is presented in Figure 3.

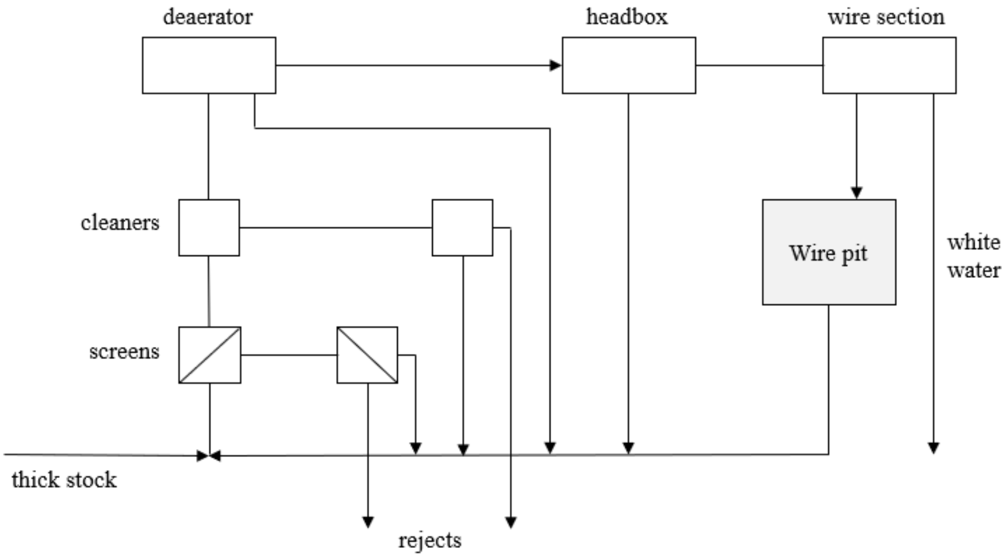

Figure 3. Conventional short circulation (Adapted from Ek et al. 2009b, 138)

Water included in the fiber slurry is removed at paper machine. Wire, press, and drying sections utilize suction to enhance dewatering process. Suction is created by vacuum pumps, which use water to seal the pump. Another fresh water inflow as cooling water is also typically needed, because the low temperature of sealing water improves the vacuum. Therefore, vacuum pumps and associated sealing and cooling water form their own water circulation called vacuum system. Modern vacuum systems can include over ten vacuum pumps and sealing water can be completely recirculated. Design of the vacuum pumps has improved and because the material of the pump can be decided according to water properties, the life cycle of the product is long despite the recirculated water. (Sweet 2000)

4.2 Long circulation

Long circulation is showed in Figure 4. Excess white water from short circulation is led to long circulation, which is used to clarify white water to be recirculated for different operations. System used for clarification is called save-all, because after separation both fiber and water streams can be reused. For instance, white water poured from wire section can be treated with a drum or disc filter, which are used to take away fines and impurities from water. Purified stream is called clarified water and it can be utilized for stock or chemical preparation and as shower water, and fiber rich water returns valuable fiber raw material back to process and works in dilution of broke. Part of clarified water is also led to wastewater treatment plant if there are excess clarified water or suitable uses for streams are not available. (Bajpai 2018, 313–317)

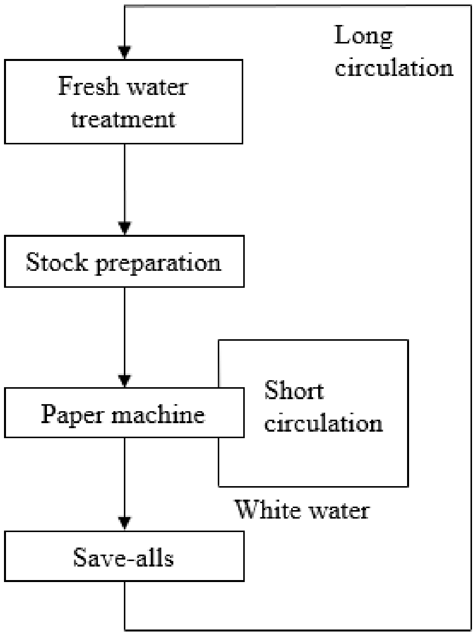

Figure 4. Long circulation (Modified from Bajpai 2018, 314)

In addition to the fiber rich water coming from the paper machine, long circulation can also process finished paper into new fiber material. Fiber recovery means reprocessing paper material, which cannot be used for the customer. Paper material used for fiber recovery is called broke and in the beginning of fiber recovery process the material is placed to pulper and treated with water. The mixture of paper and water is stirred and pulping process defibrates the paper with addition of heat or chemicals, such as furnish. Paper degradation takes approximately 30–45 minutes and is typically performed in batches. Also, continuous pulping can be performed, but complete defibering might not be reached with that technique. When pulping has degraded the paper, fiber slurry is generated, and it can be used for paper production again. (Bajpai 2018, 66–67)

4.3 Tertiary circulation

All water streams from save-alls cannot be reused within long circulation. Tertiary circulation is the outer circle at paper mill and consists of remaining water from long circulation and other water streams, which cannot be recirculated. Usually, these water streams are contaminated and are therefore led to wastewater treatment plant. These contaminated water streams are typically purified as described in section 3.4. Despite the treatment process, treated water is rarely suitable for reusing in papermaking, because high demands of the paper and local legislation are setting the requirements for the water quality. Therefore, tertiary circulation is not closed water circulation. (Bajpai 2018, 314–315)

6 Mass balance

According to principle of mass conservation mass is not destroyed or created in chemical reactions. In practice this means, that all the material flows are going somewhere, and nothing disappears. Concept of mass balance can be applied for monitoring material flows and evaluating performance of plant or unit process by mapping incoming and outcoming material. For example, efficiency of wastewater treatment plant can be assessed by analysing data related to influents and effluents. (Spellman 2016, 43–47)

Mass balance analysis is a quantitative analysis used for analyzing movement and quality of material in a system or environment. Mass balance analysis starts by drawing a schematic picture of the system of interest. An example of a picture used for mass balance analysis is presented in Figure 5. Control volume describes the changing volume within system and system boundaries are identified to delimit the area under consideration. Entering and leaving material flows are marked to schematic picture including possible transformation and accumulation of material as well. Before calculation, it should be considered if any reactions are expected to happen or is system of interest steady. After that suitable mass balance equation can be solved. Validity of the results should be inspected by verifying if the assumptions made are correct and the results are reasonable. (Howe, Hand, Crittenden, Trussell & Tchobanoglous 2012, 66–73)

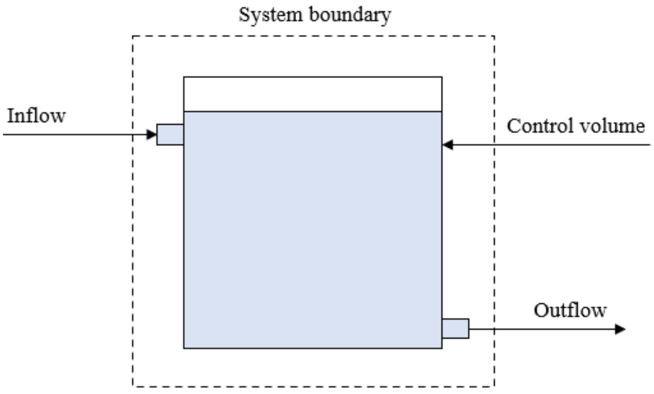

Figure 5. Simplified picture of water system for mass balance analysis (Adapted from Crittenden, Trussell, Hand, Howe & Tchobanoglous 2012, 295–297)

Material transporting through the system is called conservative, if it passes the system unchanged, or nonconservative if the material is transformed. In addition, characteristics like time and molecular forces can be taken into account depending on the scope of the analysis. It is not always necessary to examine the system in such detail in all analyses and general equation is sufficient. (Crittenden et al. 2012, 295–297)

$$In - out - loss + generation = accumulation \qquad (1)$$

where *In* is mass of material entering system, *out* is material leaving the system, *loss* is disappearing from the system, *generation* is mass of material generated in the system and *accumulation* is accumulation of material in system. Equation 1 is simplified mass balance equation illustrating the transportation of material through the system. Details of the reactions should be considered separately. (Crittenden et al. 2012, 295–297)

Accordingly, paper mill water and mass flows can be calculated

$$q_m + q_f = q_v + q_p + q_e \qquad (2)$$

where q_m is pulp flow entering the paper mill, q_f is fresh water flow entering the paper mill, q_v is water losses through ventilation, q_p is manufactured paper product and q_e is the effluent leaving the paper mill. Therefore, Equation 2 summarizes total balance of the paper mill. If water and material flows of paper mill unit processes, such as short or long circulation, are studied separately, information on circulating water flows is required as well. For example, flow rates, consistency of the fiber slurry and retention should be known. (Ek et al. 2009b, 104–117)

APPLIED PART

7 Water fractions at PM1

This section introduces water fractions used at PM1. Usage of mechanically purified water, chemically purified water, white water, and process wastewater are briefly explained to provide relevant information for mapping of water circulations. Main properties of these water fractions are summarized in Table 4.

7.1 Mechanically purified water

Mechanically purified water is used while producing unbleached paper products. Mechanically purified water is used also while manufacturing bleached paper grades to destinations which are not in contact with raw materials, such as sealing water and cooling water. For example, mechanically purified water is used in PM1 vacuum system to provide vacuum and keep the system cool. Mechanically purified water used at PM1 is taken from lake Luodonjärvi and there is no specification for the water quality. Mechanically purified water is screened before it is pumped to PM1.

7.2 Chemically purified water

Chemically purified water is purchased from external supplier and pumped straight from the water plant into PM1. Chemically purified water is used during manufacturing process of bleached paper products, for instance diluting bleached fiber slurry and cooling wire pit. In addition, chemically purified water is used at warm water system nevertheless bleached or unbleached products are in the manufacturing. Specification for chemically purified water is presented in Table 2.

Table 2. Specification for chemically purified water

pH	**conductivity [mS/m]**	**KMnO4 cons. [mg/L]**	**Iron [mg/L]**	**Manganese [mg/L]**	**Copper [mg/L]**	**Chloride [mg/L]**	**Color [mg/L]**
7.0–8.5	< 20	< 16	< 0.10	< 0.10	< 0.01	< 30	< 20

7.3 White water

White water circulates in short circulation, stock preparation and broke system to collect valuable fiber raw material for paper production. There are more data related to white water available, because quality control laboratory is analysing white water fiber content regularly and temperature can be continuously measured from wire pit. White water is stored at circulation water tower, white water tank, white water pit and suction water pit.

7.4 Process wastewater

Process wastewater contains those water fractions, which are removed from water circulations and lead to wastewater channel. Wastewater emission levels are controlled via environmental permit and service agreement between Billerud Pietarsaari Mill and wastewater treatment service provider. These limits are presented in Table 3.

Table 3. Emission limit values for PM1 wastewater.

Parameter	**Emission limit value [mg/L]**
Solid matter	< 2000
COD	< 2800
pH	6–8
Total nitrogen	< 3
Total phosphorus	< 0.3

Solid matter, COD, BOD7, total nitrogen and total phosphorus are analysed once a week and reported monthly according to environmental permit. AOX is analysed and reported 4 times a year. Continuous flow and pH measurements for process wastewater are performed.

7.5 Summary of water fractions

Mechanically purified water, chemically purified water, white water, and process wastewater are relevant water fractions for mapping water circulations and mass balances at PM1. White water is in a different position compared to chemically purified water, as it is produced as a result of the paper manufacturing process, while chemically purified water is purchased from an external supplier. Therefore, specification for chemically purified water has been set by the supplier, while white water quality is controlled by PM1 employees. Applicable and available parameters of each water fractions are summarized in Table 4.

Table 4. Summary of water fractions

Water fraction	**Temperature [°C]**	**Fiber content [mg/L]**	**Flow [L/s]**
Mechanically purified water	Not available	Not applicable	64
Chemically purified water	Not available	Not applicable	49
White water	53	95	Not available
Process wastewater	Not available	272	98

7.6 Data collection

Chapter 7 starts the applied part of the master’s thesis by introducing the water fractions used at PM1. The applied part continues with mapping of water circulations, flow rates and mass balances. Water fractions mentioned in this chapter are investigated closer as a part of water circulations and PM1 mass balance. For this investigation, data related to these water fractions have been collected from the process control system. Continuous flow measurement of the water streams is measured with electromagnetic flow meters at PM1.

Measurement data is collected every fifth second to process control system, from where an eight-hour average of data points have been exported to Excel. Based on the eight-hour averages, an annual average of flows and standard deviations have been calculated. Mapping of the water circulations and flow rates contains 37 flow measurement points, which are identified in figures presented in chapter 8 and listed in chapter 9. These data points are consisting of white water, mechanically purified water, chemically purified water, process wastewater and shower water flows.

The variation in the collected flow data was also looked at on an annual basis. Due to the large variation in flow rates, variation was examined based on the range of the flow. Standard deviations were calculated to all water streams, for which flow rate data was available. Those water streams, which flow rate was > 100 L/s had standard deviation of ± 34 L/s, water streams with flow rate of > 10 L/s < 100 L/s had standard deviation of ± 15 L/s and the water streams with flow rate of < 10 L/s had standard deviation of ± 1.5 L/s.

8 Mapping of water circulations

This section describes water circulations at PM1. The aim of this chapter was to map water flows and investigate what kind of flow rate data for each water fractions there is available. Sealing water flows are out of the scope of this mapping, because even though the amount of the sealing water flows is high, they represent only a minor amount compared to the total flow used in the paper manufacturing process. The flow rates presented in this mapping are annual averages from 2021.

8.1 Short circulation

PM1 short circulation is presented in Figure 6. Water streams are identified by numbers and flow rates are presented in Table 5. Short circulation at PM1 begins from machine chest, where fiber slurry is diluted with white water from suction water pit. The diluted slurry is pumped to wire pit and either chemically or mechanically purified water is added to the wire pit to decrease the temperature of the fiber slurry. Heavy particles are removed with five step hydrocyclone system, which is able to remove approximately 96% of > 100 µm particles. The accept from stage one hydrocyclone has high enough quality properties to be used to paper manufacturing and is treated with deaeration system before head box. The accept from stage two goes back to stage one feed. Correspondingly, stage three accept is lead back to stage two feed, as well as stage four accept to stage three feed and stage five accept to stage four feed. The reject from stage one continues to stage two, stage two reject to stage three, stage three reject to stage four and stage four reject to stage five. The rejects from stages three, four and five are diluted with white water from wire pit. Finally, stage five reject is drawn out to waste water channel.

There are also three screens with hole diameter 2.4 mm in short circulation, before entering head box. The accept from primary screen continues to head box and reject is screened again with secondary screen. The accept from secondary screen is pumped to stage one hydrocyclone to be purified and reject is screened once more with reject screen. The accept from reject screen goes back to secondary screen and reject from reject screen is drawn out to waste water channel. Part of the water used is lost in drying section and approximately 7% moisture remains in the final product.

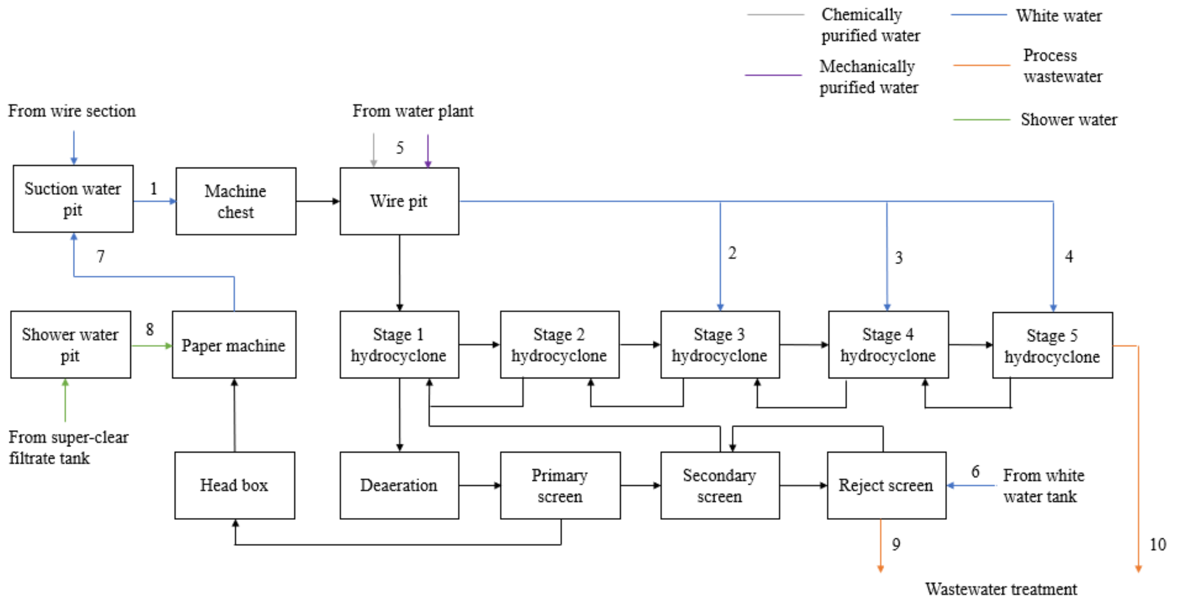

Figure 6. PM1 short circulation. More information about the specified streams is given in Table 5.

Table 5. PM1 short circulation water flow rates

No.	Water stream	Water fraction	Flow [L/s]
1	Stock dilution	White water	118
2	Hydrocyclone 3 dilution	White water	8
3	Hydrocyclone 4 dilution	White water	3
4	Hydrocyclone 5 dilution	White water	1
5	Wire pit cooling water	Chemically or mechanically purified water	18
6	Reject screen shower water	White water	Not available
7	Water from wire section	White water	Not available
8	Wire and press section shower water	Super-clear filtrate	3
9	Reject screen reject	Process wastewater	2
10	Hydrocyclone 5 reject	Process wastewater	4

As mentioned above, short circulation water flows presented in Figure 6 consists of stock dilution, hydrocyclone dilutions and wire pit cooling water. The stock and hydrocyclones are diluted with white water, but wire pit cooling water is either chemically or mechanically purified water depending on if bleached or unbleached paper is manufactured. Water used for wire and press section shower water is super-clear filtrate from shower water pit. The outflows are rejects from reject screen and hydrocyclones.

Flow rate measurements are not available for reject screen shower water or for the water from the wire section, which is circulating back to the short circulation. Approximately 157 L/s of white water circulates in short circulation and 3 L/s of super-clear filtrate is recirculated to short circulation via wire and press section showers. 18 L/s of mechanically or chemically purified water is used for wire pit cooling. The combination of process wastewater flows pumped to the wastewater treatment plant is approximately 6 L/s.

8.2 Stock preparation

Stock preparation at PM1 is introduced in Figure 7. Water streams are identified by numbers and flow rates are presented in Table 6. As PM1 is located in integrated mill area, utilities like fresh water treatment are part of service agreement between PM1 and other service providers. PM 1 purchases water and process waste water treatment services from external supplier, which is responsible of chemical and mechanical purification of the fresh water. Therefore, fresh water treatment is not part of PM1 long circulation. Stock preparation begins from bleached or unbleached thick stock pulp towers, where white water from white water tank is added on the bottom of the tower to dilute the stock and make the pumping more efficient. Consistency of pulp in thick stock pulp tower is approximately 10%, so large part of the incoming water is included in the pulp. Consistency of stock decreases while getting closer to paper machine, so dilution of stock with white water is performed in pulp chests, middle chests, and machine chest. There are two pieces of pulp and middle chests, but pulp chest 1 is used only if high consistency (HC) refiners are used. This is illustrated with dotted line in Figure 7. During these steps, the stock is treated with additives and fibers are modified by refining as well.

There are no waste water flows from stock preparation, because stock preparation is combined with other water circulations at paper mill. Water passes the stock preparation to the wire pit via short circulation through the wire section. Excess water from wire pit pours to vacuum water pit, from which excess water pours to white water tank. Water from white water tank is used for disc filter, so the outflow from stock preparation can exit as clear filtrate via broke system or used for stock dilution again. Thick stock screening can be used for foreign material removal if it is needed to achieve desired quality for paper. There are two thick stock screens, which removes impurities > 250 µm before machine chest. Stock from the middle chest 2 is pumped for screening and the accept from the first stage thick stock screen goes to middle chest 1. White water is used to dilute feed at both screens and as backwash-water. The reject continues to the second thick stock screen, from where the accept is lead back to the first thick stock screen and the reject is either pouring to waste water channel or is pumped to the broke chest. Also, this thick stock screening is illustrated with dotted line, because it is not in use all the time.

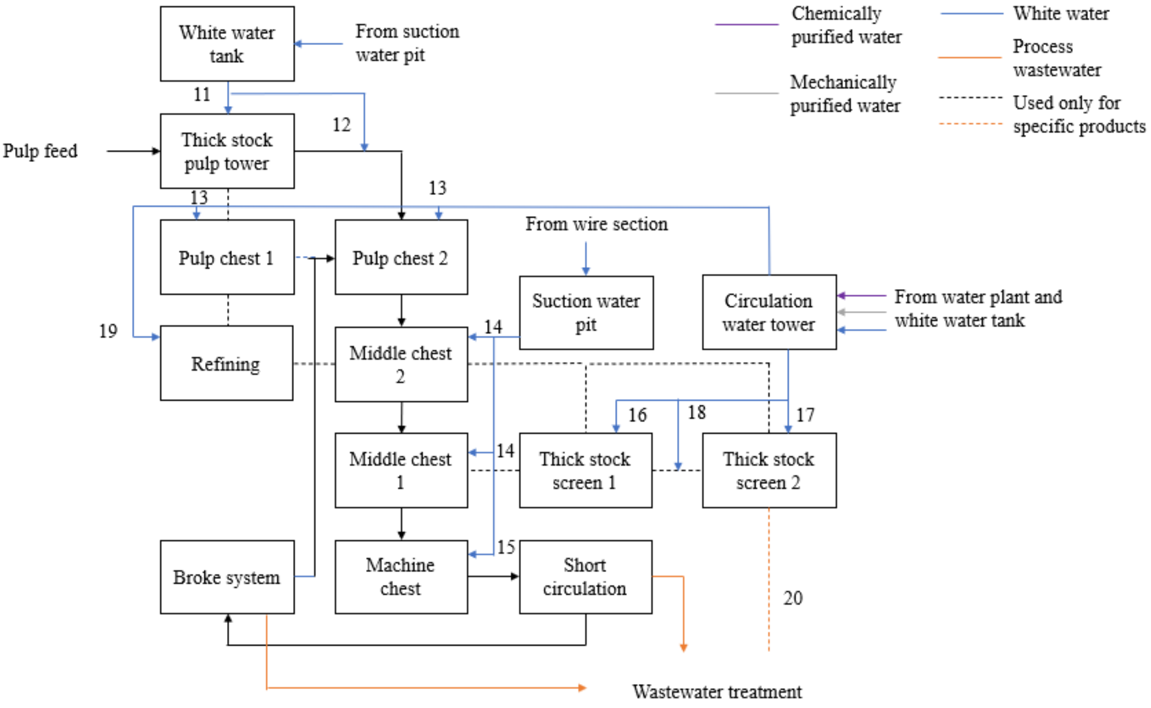

Figure 7. PM1 stock preparation. More information about the specified streams is given in Table 6.

Table 6. PM1 stock preparation and broke system water flow rates

No.	Water stream	Water fraction	Flow [L/s]
11	Thick stock bottom dilution	White water	25
12	Thick stock dilution	White water	14
13	Pulp chest dilution	White water	36
14	Middle chest dilution	White water	23
15	Machine chest dilution	White water	118
16	Thick stock screen 1 dilution	White water	6
17	Thick stock screen 2 dilution	White water	4
18	Thick stock screen 2 feed dilution	White water	9
19	Refiner dilution	White water	34
20	Thick stock screen reject	Process wastewater	1

As described, stock preparation consists of water streams, which are used to modify pulp for required properties. White water is used in several steps to dilute the stock to suit each step, such as for screening and refining. The process wastewater flow collected to wastewater channel is the reject from the thick stock screen.

Therefore, there are approximately 409 L/s of white water circulating at stock preparation and broke system. Only 1 L/s of process wastewater is exiting to the wastewater treatment plant, because most of the water in fiber slurry ends up in short circulation. As stock preparation is connected to short circulation and broke system, process wastewater is exiting PM1 via streams identified by number 9 and 10 in Table 5 and 29 in Table 7.

8.3 Broke system

PM1 broke system is illustrated in Figure 8. Water streams are identified by numbers and flow rates are presented in Table 7. Broke consists of web breaks and reel change broke from pope reel pulper, edge trims and web breaks from press section pulper and edge trims from winder pulper. In addition, broke reels can be disposed through broke system. Broke from these sources ends up to broke tank, from where broke is pumped to broke tower. Dilution water to broke tank is white water and process water to broke tank. Broke is pumped to disc filter where it is needed to ensure purification of water. White water is used to dilute broke pumped to disc filter. Disc filter divides the fiber slurry into three different fractions, cloudy, clear, and super-clear filtrates and drill manipulates fiber rich part of broke, which is diluted with white water.

Cloudy filtrate is diluted with white water lead back to disc filter to collect fibers for paper raw material. Clear filtrate is collected to white water tower to be used for the dilution of incoming pulp. If all clear filtrate produced cannot fit into white water tank, it overpours to waste water channel. Super-clear filtrate is stored in shower water tank, and it is used as shower water at wire and pressure sections, since it includes only low concentration of fibers. Fiber rich broke from disc filter is stored in fiber recovery tank with addition of white water. Then broke is pumped to broke chest and diluted with white water. Water from wire and pressure section circulates back to broke tank through broke, so broke system is connected to short circulation as well.

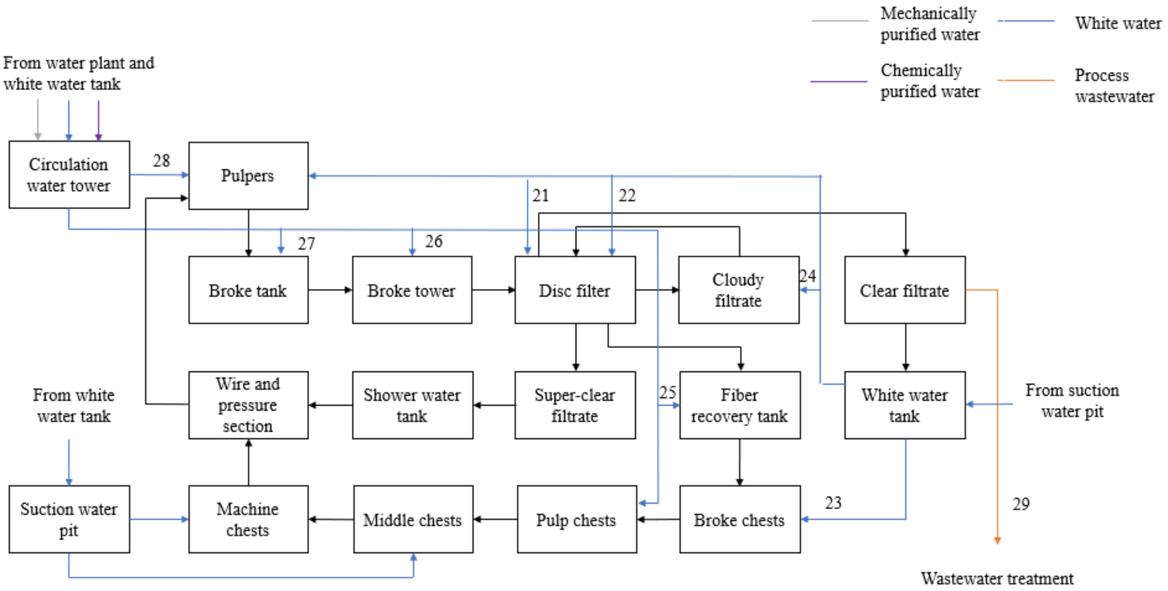

Figure 8. PM1 broke system. More information about the specified streams is given in Table 7.

Table 7. PM1 broke system water flow rates

No.	Water stream	Water fraction	Flow [L/s]
21	Disc filter dilution	White water	128
22	Disc filter drill dilution	White water	12
23	Broke chest dilution	White water	Not available
24	Cloudy filtrate dilution	White water	Not available
25	Fiber recovery dilution	White water	Not available
26	Broke tower dilution	White water	Not available
27	Broke tank dilution	White water	Not available
28	Pulper dilutions	White water	Not available
29	Clear filtrate	Process wastewater	25

Flow rates measured from broke system are 140 L/s of disc filter dilutions and clear filtrate outflow of 25 L/s. Stock preparation and broke system mapping stated that there are no measured flow rate data regarding broke material dilution. This consists of broke chest dilution, cloudy filtrate dilution, fiber recovery dilution, broke tower dilution, broke tank dilution and pulper dilutions. It can be assumed that approximately 115 L/s of the white water is circulating in the broke system.

8.4 Long circulation

Short circulation, stock preparation and broke system are connected, so they will be investigated combined later in this mapping. Figure 9 simplifies PM1 long circulation and shows how water flows of stock preparation, short circulation and broke system are connected via white water system. Water streams are identified by numbers and flow rates are presented in Table 8.

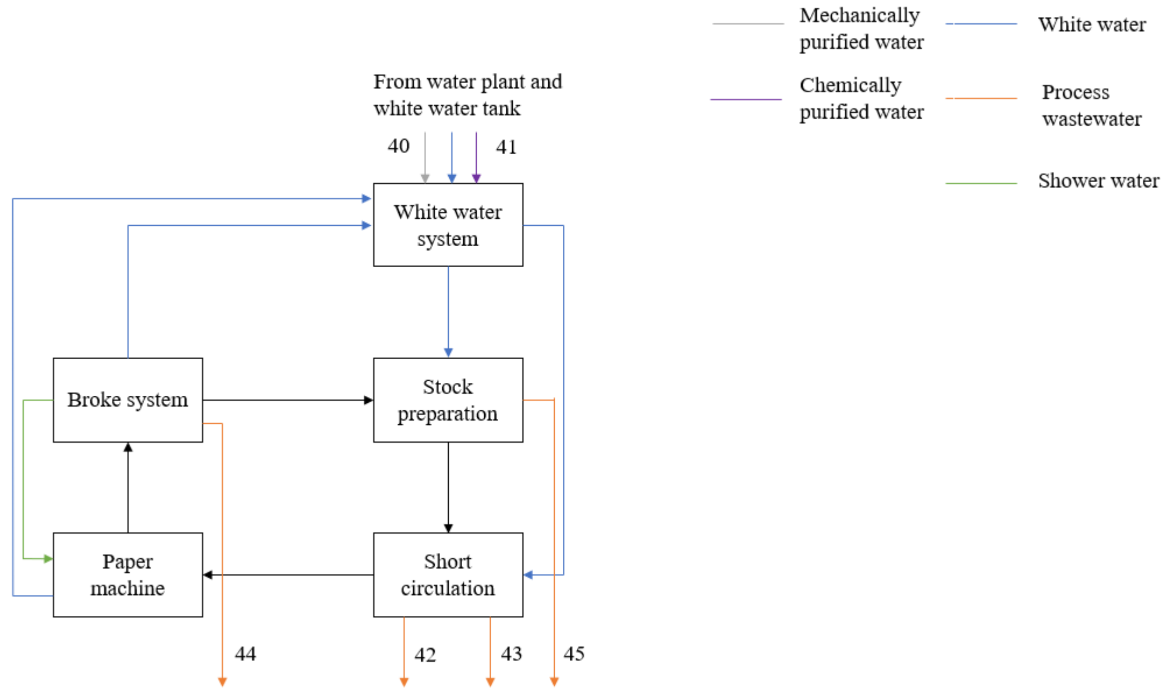

Figure 9. PM1 long circulation. More information about the specified streams is given in Table 8.

Table 8. PM1 water flow rate summary

No.	**Water stream**	**Water fraction**	**Flow [L/s]**
40	Mechanically purified water	Mechanically purified water	64
41	Chemically purified water	Chemically purified water	49
42	Reject screen reject	Process wastewater	2
43	Hydrocyclone 5 reject	Process wastewater	4
44	Clear filtrate	Process wastewater	25
45	Thick stock screen 2 reject	Process wastewater	1
46	From vacuum system	Mechanically purified water to rainwater well	Not available

PM1 paper manufacturing process was divided into three systems for mapping of water flow rates. A lot of data regarding white water flow rates circulating in the water circulations were found, but there was only limited amount of data to track how much chemically, and mechanically purified water has been used in each unit processes. Therefore, consumption of chemically and mechanically purified water streams has been investigated on PM1 level. This summary does not include white water fractions, because it can be assumed that the white water fractions mentioned in Tables 5, 6 and 7 are mostly recirculating in short circulation and long circulation.

It can be seen, that mechanically purified water flow to PM1 is 64 L/s and chemically purified water stream is 49 L/s. Total amount of process wastewater pumped to wastewater treatment plant is 32 L/s and the amount of mechanically purified water led to rainwater well is 12 L/s.

8.5 Vacuum system

Mechanically purified water used at PM1 vacuum system constitutes water circulation, which provides water for vacuum pumps located at wire, press and drying sections and deaeration unit. PM1 vacuum system is presented in Figure 10 below. Water streams are identified by numbers and flow rates are presented in Table 9.

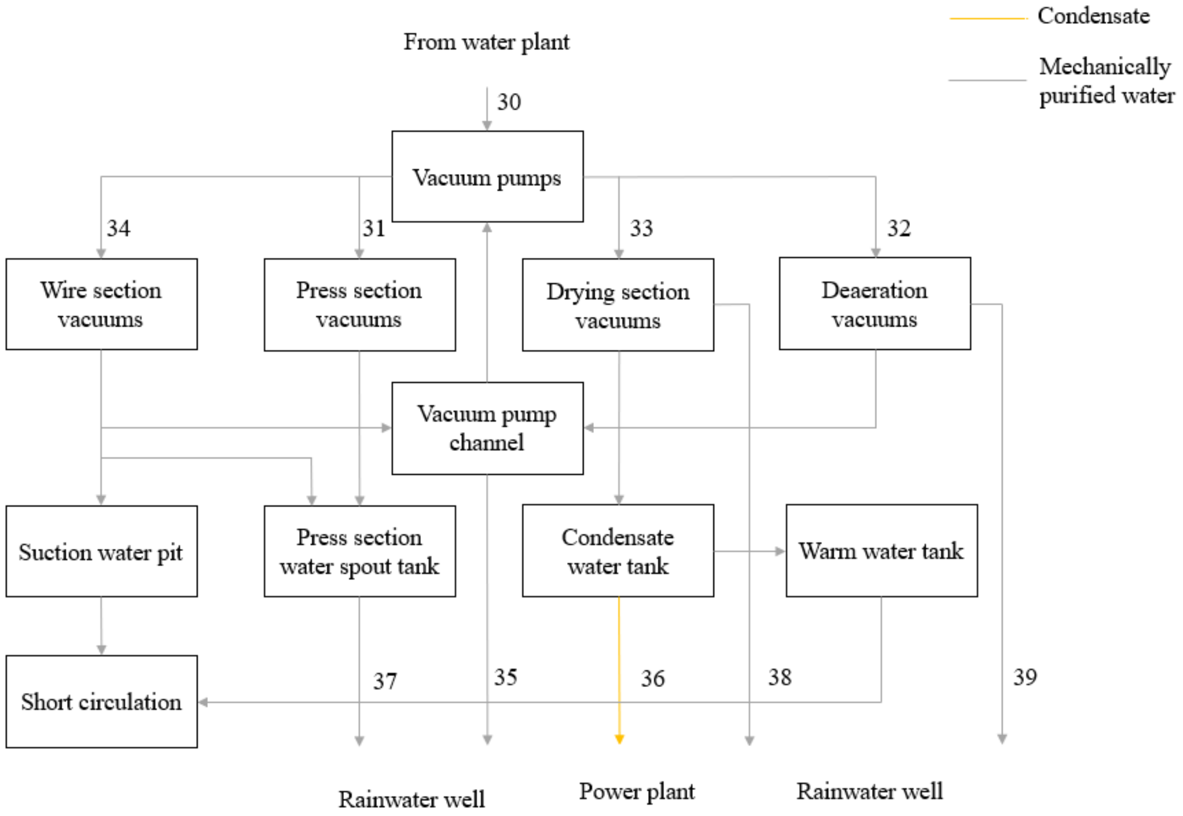

Figure 10. PM1 vacuum system. More information about the specified streams is given in Table 9.

Table 9. PM1 water flow rate data summary

No.	Water stream	Water fraction	Flow [L/s]
30	Vacuum pump cooling water	Mechanically purified water	12
31	Press section vacuum pump water	Mechanically purified water to rainwater well	Not available
32	Deaeration vacuum pump water	Mechanically purified water to rainwater well	Not available
33	Drying section vacuum pump water	Mechanically purified water to rainwater well	Not available
34	Wire section vacuum pump water	Mechanically purified water to rainwater well	Not available
35	Vacuum pump channel water	Mechanically purified water to rainwater well	Not available
36	Heat recovery system condensate water	Condensate to power plant	Not available
37	Press section water spout tank water	Mechanically purified water to rainwater well	Not available
38	Drying section vacuum water	Mechanically purified water to rainwater well	Not available
39	Deaeration vacuum water	Mechanically purified water to rainwater well	Not available

Mechanically purified water is fed to liquid ring vacuum pumps, and they pour water into vacuum pump channel circulating water back to the vacuum pumps. Excess water from the vacuum system pours into rainwater well since it does not require purification at wastewater treatment plant. Water removed from wire section is lead to suction water pit and waterspout tank. Water from suction water pit circulates back to short circulation. Water removed from press section pours to press section waterspout tank. Water from drying section, for its part, goes to wastewater channel. Warm condensate water from drying section is pumped to integrate power plant and minor flows for center roll blade and as calender cooling water. Water from deaeration system vacuum is lead either into vacuum pump channel or wastewater channel.

As can be seen, vacuum system inflows and outflows are mainly mechanically purified water. Mechanically purified used as cooling water circulates to different parts of paper machine and exits via vacuum pump channel, wire section and drying section vacuums or deaeration unit vacuum, which are led to rainwater well. In addition, drying section vacuum pump water is connected to heat recovery system, from where warm condensate is pumped to power plant.

Vacuum system takes approximately 12 L/s of mechanically purified water and flow rates for mechanically purified water exiting the system to rainwater well are not controlled. Warm condensate flow rate is not measured either, so only known water stream related to vacuum system is the inflow.

9 Mapping of mass balances

Due to the limited amount of data regarding chemically and mechanically purified water flow rates entering short circulation, stock preparation and broke system, it was not possible to map mass balances for those unit processes separately. Therefore, PM1 mass balance has been examined as a whole. Vacuum system is presented separately because it is independent water circulation.

9.1 Vacuum system mass balance

Vacuum system mass balance involves one mechanically purified water inflow, which is 12 L/s. Outflows are not controlled. Vacuum system temperature is not that high, that water evaporation would be expected. It can therefore be assumed that the volume of losses in the process is minimum and approximately same amount of water would be exiting vacuum system to rainwater well. PM1 vacuum system mass balance analysis is illustrated in Figure 11. These values are considered as a part of PM1 mass balance in chapter 9.2.

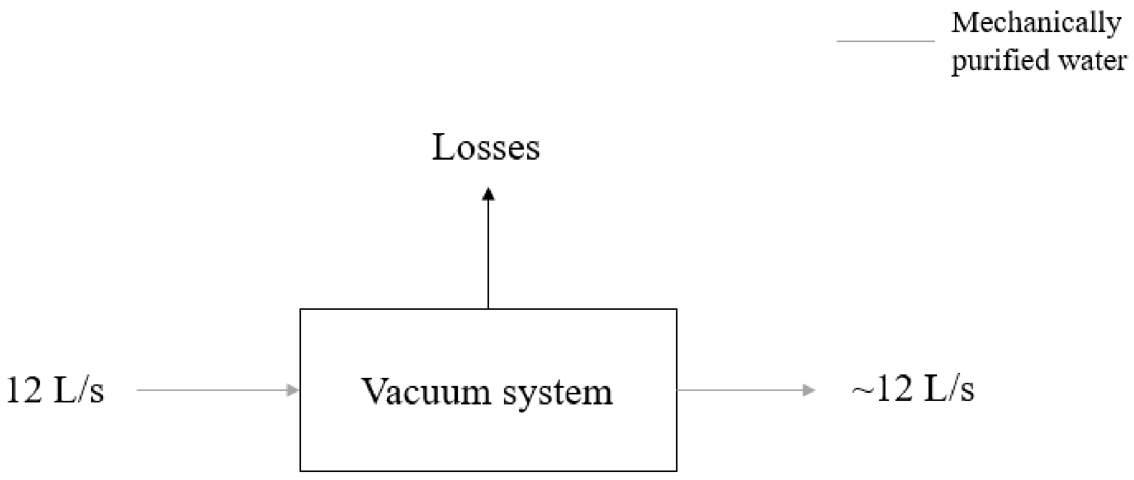

Figure 11. PM1 vacuum system mass balance analysis

9.2 PM1 mass balance

PM1 mass balance analysis is presented in Figure 12. Water inflows to PM1 are consisting of mechanically purified water and chemically purified water. Mechanically purified water flow is 64 L/s and chemically purified water flow is 49 L/s, which makes total inflow 113 L/s. It has not been possible to exclude the sealing water flows from the mechanically purified water inflow, even though it was not in scope of this mapping. Incoming pulp feed includes approximately 90% of water, which brings approximately 63 L/s water input to the process. This water fraction is mainly ending up recirculating in short and long circulation. Typical value for finished paper moisture content is approximately 7%, so dewatering process is not removing all the water. Water input in finished paper is approximately 0.5 L/s. Water that ended up in finished paper can be originated from either water input from pulp feed, chemically purified water, or mechanically purified water. Some of the chemically and mechanically purified water used also ends up as part of the white water circulation through the paper manufacturing process. According to mass balance analysis it can be estimated that approximately 125 L/s of white water ends up back to water circulation. This would mean, that approximately 71% of incoming water is recirculated at PM1.

PM1 process wastewater flow is 32 L/s and if it is assumed that the outflow from the vacuum system is 12 L/s, total outflow from PM1 is 44 L/s. It can be expected that the flow rate for mechanically purified water exiting PM1 is 6 L/s higher, because mechanically purified water is used as sealing water, and it is led to process wastewater channel as well.

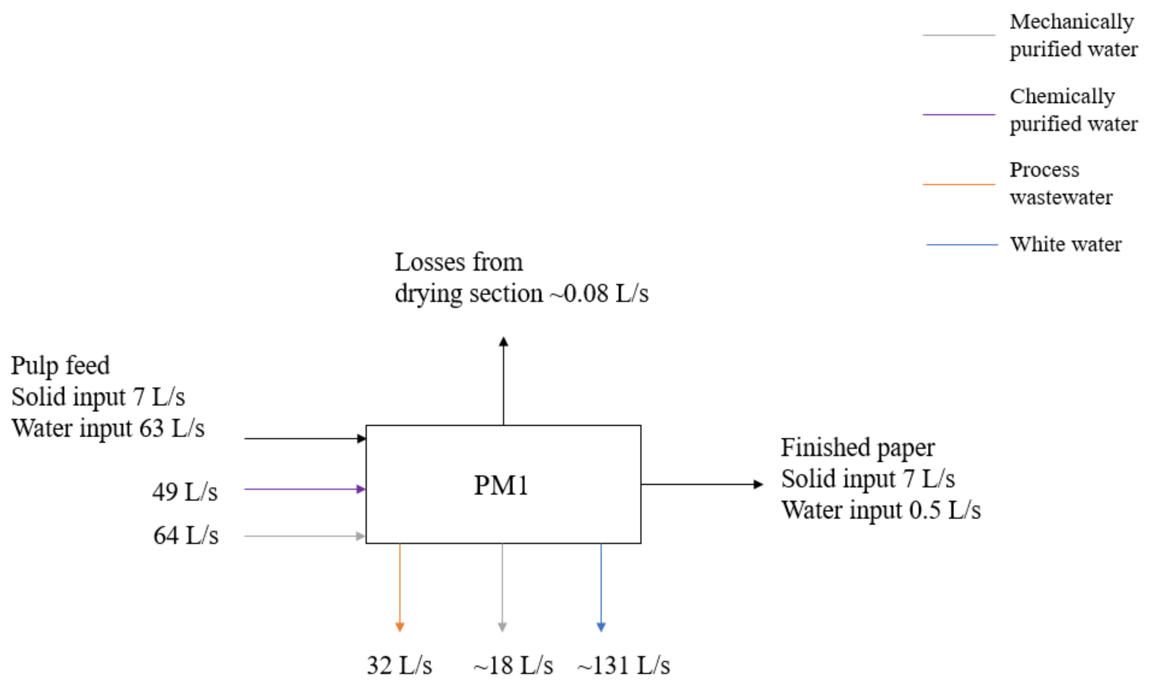

Figure 12. PM1 mass balance analysis

In addition to the calculated flows, it has been identified that water is lost in the dying section as a result of evaporation. According to Chen, Zheng & Dong (2021) approximately 1.1–1.3 kg of water evaporates per kg of paper production in drying section. Based on this theoretical value, it could be calculated that the volume of losses from drying section is approximately 0.08 L/s.

10 Results and discussion

Mapping of water circulations found that approximately 71% of the incoming water is already recirculated in paper manufacturing process. Chemically purified water consumption in 2021 was 10 m^3/ADt and mechanically purified water consumption was 11 m^3/ADt. Aiming for zero liquid discharge water system would not be the optimal way for PM1 to reduce water consumption, because the products have high microbiological quality demands. The mapping of water circulations stated that there are mechanically purified water streams, such as sealing waters, which are mixed with process wastewater and lead to wastewater treatment plant. From an economic point of view, this provides a saving potential, as it would not be necessary to pump mechanically purified water to wastewater treatment plant, because it is only mechanically screened fresh water. The mapping of water circulations was followed by the mapping of water flow rates, which involved a lot of work related to data collection. This gave a good compilation of the size range of the different water flows, which will help in the future to continue the work and set the water reduction actions to significant flow streams. For example, it could be useful to investigate if the wire pit could be cooled with some other technique than mixing chemically or mechanically purified water with wire pit water.

The greatest challenge during the work proved to be the limited amount of available data. The direction of the mapping changed during the master's thesis process, when it was discovered that the flow rate data was not available with the desired accuracy. For example, it was not possible to make water balance analysis for different unit processes with the precision that was initially hoped. The limited flow rate data was mainly concerned with streams of chemically purified and mechanically purified water, which was limiting the possibilities to analyze incoming fresh water flows to different unit processes. However, for the future, it is necessary to consider whether this information is relevant for the assessment of the environmental impacts, because installation of flow meters on large pipes is expensive. The mapping of mass balances can still establish the groundwork for creating a new practice and a point of view, in which water consumption is viewed through incoming and outgoing water flows.

The background of this master’s thesis was to act as a groundwork to LCA tool, which will require data regarding water consumption at PM1. Awareness of the available data increased, which also makes it possible to estimate how water consumption differs between different product groups. In the production of unbleached paper, water consumption consists mainly of mechanically purified water and, when producing bleached paper, mainly from chemically purified water. Chemically purified water is more expensive of these because it has been treated more. The water consumption of paper grades increases with the demands of the final product or the more processing the mass requires. For instance, HC refining and thick stock screening are not necessary processes for all the paper grades, and those will affect to product specific water consumption.

The water consumption of the product is mostly based on customer requirements. These demands have to be met, so the main tool for reducing water consumption is process optimization so that no excessive water is used to make the product. Process optimization provides environmental benefits and lower water consumption also means financial savings. Process optimization would support company's environmental goals as well.

11 Conclusions and future research

Sustainable future is a strategic direction of Billerud. The environmental impact assessment of the factories allows that information about paper product sustainability can be offered to the customers. PM1 manufactures a wide range of paper products, which makes it more difficult to provide product specific data regarding environmental impacts. Development of LCA tool provides a unique possibility for Billerud to take notice of changes in the manufacturing process and provide up-to-date environmental data for the customers.

The mapping found that PM1 has enough information on water consumption for the LCA tool. The accuracy of the data is also sufficient to make a product specific life cycle assessment and it will be easier to collect and evaluate the data when the mapping has been performed. However, mapping of water circulations and the mass balance pointed out that there are other targets, such as reduction of water consumption, that could benefit from development of water usage monitoring.

The focus on this issue has also given a perspective on what level the accuracy of data needs to be collected and how the water consumption should be monitored. It is not meaningful to add flow measurement to all the missing pipe lines, even if all the data was not available for this mapping. PM1 has set a goal for reducing chemically purified water consumption and therefore possible actions could be directed to monitoring it. Flow meters and their installation is a large cost, as mentioned earlier, and the information gathered from all pipes would not necessarily end up being exploited. The measurement results are calibrated by collaboration between laboratory staff and maintenance workers, so each new meter also creates new responsibilities. This makes it particularly important that the real need is mapped before investment decisions are made. There are portable flow meters, which would allow PM1 collect data from that kind of data collection points, which are not normally controlled. Purchasing of portable flow meter could help to solve fault situations and provide more information for development projects.

The collection of data related to water circulations at paper machine took a lot of time, because information regarding water circulations was located around process control system and there was no one place, where it would have been easy to see everything at one time. It would be beneficial to have all water circulations in one page to see the big picture.

Modelling water cycles would make it easier to collect the information and increase the overall knowledge of water circulations. This increase in knowledge would make the employees across the organization to pay more attention to water usage and, as a result of this to contribute to achieving water consumption reduction goals. It would also be useful to create a visual tool for monitoring water consumption. Even though the flow data is available currently, a visual tool could make monitoring the consumption more efficient and make it faster to react to changes in consumption levels.

For further research, it is important to remember that water consumption is linked to many aspects of the paper mill. Potential investments should also be considered comprehensively, as, for example, process digitalization or changes to increase production or energy efficiency can also achieve a reduction in water consumption.

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