Circular water management in breweries

Can the process effluent of a brewery be used to grow oranges?

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Using the water pinch analysis to optimize the water network of a brewery and its neighbours to achieve circularity

By

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Preface

Environment, sustainability, responsible water use are important topics these days. Especially with the rising concerns about climate change, water has become one of the main resources that is endangered. Within the study Environmental Engineering I came across all water related topics and I was shown what role we can play as an engineer. I feel the responsibility but also the joy that I can play a role in restoring the balance of the environment to make our planet a liveable place for, hopefully, many years.

This thesis concludes my master's degree in Environmental Engineering at Delft University of Technology. It was carried out at Heineken, which gave me the opportunity to work inside a multinational and use their facilities to conduct my research. Working at Heineken gave me not only insight in the brewing industry but it also provided me experience with working in a company that is widely spread over the world. It gave me insight in what I like in a working environment, which will definitely help me during my next phase, the adult working life!

I would like to thank Paul Bruijn, as my daily supervisor at Heineken. Thank you for giving me the freedom to work on my own project and guide me when necessary. Besides, I would like to thank all the other employees at the Heineken Global Sustainability, Utilities and Environment team. A special thanks to the other interns at the team, it was nice to share the 'intern life struggles' with each other.

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Lastly, I would like to thank my family and friends. It has not always been easy during the thesis and you have helped me in all different ways to make sure that I kept going.

Noor Holland
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Abstract

Water is an important resource in many industries in the world. Due to emerging regulatory framework, change in consumer's perspective and increasing costs for water, industries are forced to move towards sustainable water use. Nowadays, improvements in the brewery industry are focussed on increasing the efficiency of the processes or treating the complete wastewater stream on site. Water network optimization models can effectively decrease the fresh water flowrate and wastewater flowrate production. The water pinch is in most cases used to optimize fresh water use and wastewater production in a single industry. This thesis is the first to use the water pinch in a circularity concept of a wider network with a brewery and external user. Circularity is in this thesis defined as the percentage of water from a brewery that can be reused by an external party, after it has been used inside the brewery.

Two case breweries in Egypt were used to illustrate the water pinch method, El Obour brewery and Sharkia brewery. For both breweries an orange orchard of 87 ha with a water demand of 9836 m^3/month was indicated as the external user. Per brewery, a list of water using processes that produce an effluent was determined. This list contains the CIP processes in the brew house and cellars and includes every process in the packaging department. In addition, the utility department processes cooling towers, boilers and CO_2 washers were part of the water network of the breweries. The initial water network of El Obour consisted of 18 brewery processes and one external user, the orange orchard. Sharkia brewery had 17 brewery processes and the orange orchard. Actual process water flowrates were used as well as UBM process water flowrates. For El Obour brewery the initial fresh water flowrate was 9755 m^3/month and 8466 m^3/month for UBM process water flowrates. The Sharkia brewery initial fresh water flowrate was 15695 m^3/month and 14961 m^3/month for UBM process water flowrates.

COD, Total N and Na^+ were identified as key constituents. Per key constituent, a composite curve was constructed and a new, optimized water network designed. For the El Obour brewery the water pinch steps were described in detail to show how the composite curves and the networks could be constructed. The Sharkia brewery was used to validate the method. With the composite curve and pinch point determined, processes could be indicated as source or sink. The orange orchard was always considered as a sink and was satisfied first with every possible source. The water that was flowing from the brewery to the orange orchard identified the circularity potential of the network. COD was the reference constituent for both breweries as the most restrictions occurred in this network. With the COD limiting network as basis, integrated networks were designed that complied with every constituent restriction. The results showed that for El Obour the fresh water consumption decreased with 7% to 7909 m^3/month and the wastewater production decreased with 22% to 6607 m^3/month. Resulting in an initial circularity potential of the El Obour brewery of 11 – 13% (depending on the used process water flowrates based on actual measurements or UBM). The fresh water consumption and wastewater production savings for Sharkia were respectively 0% and 34%. The Sharkia brewery could be 28 – 34% circular on water in the initial phase without treatment of effluents (depending on the used process water flowrates based on actual measurements or UBM). 100% circularity could not be achieved due to too high Na^+ and COD concentrations. Total N caused no restrictions for reuse.

The results show that the water pinch can be used to determine to what extend the case breweries can be circular on water with an external user. The water pinch is not only an optimization tool but it can help industrial sites including a brewery to identify collaboration between different users of the local watershed. Hereby increasing the circularity on water.

Contents

Nomenclature

List of acronyms

BMF	Beer Membrane Filter
CE	Circular Economy
CIP	Cleaning In Place
COD	Chemical Oxygen Demand
CSTR	Continuous Stirred Tank Reactors
EGSB	Expanded Granular Sludge Bed
FAO	Food and Agriculture Organization
FST	Fermentation and Storage Tank
Ha	Hectares
hL	Hectolitres
HORAP	Horizontal Fermentation Tank
KOH	Potassium Hydroxide
LSI	Langelier Saturation Index
MBR	Membrane Bioreactor
MINLP	Mixed Integer Non-Linear Program
N	Nitrogen
Na^+	Sodium
NaOH	Sodium Hydroxide
PET	Polyethyleentereftalaat
PVPP	Polyvinylpolypyrrolidone
RO	Reverse Osmosis
SDG	Sustainable Development Goals
THMs	Trihalomethanes
UASB	Upflow Anaerobic Sludge Blanket
UBM	Utility Bench Mark
WCA	Water Cascade Analysis
WHO	World Health Organisation
WWTP	Waste Water Treatment Plant

List of symbols

$C_i^{lim,in}$	mg/L	Limiting inlet concentration of constituent in water for process i
$C_i^{lim,out}$	mg/L	Limiting outlet concentration of constituent in water for process i
C_j	mg/L	Constituent concentration in interval *j*
$C_{sink,in}$	mg/L	Inlet constituent concentration for a sink
$C_{source,out}$	mg/L	Outlet constituent concentration for a source
f_i	m^3/month	Limiting water flowrate of process i
f_j	m^3/month	Water flowrate in interval *j*
f_p	[m^3/h]	Water flowrate in process p
$f_{ws,j}$	m^3/month	Fresh water flowrate in interval *j*
$f_{ws,min}$	m^3/month	Minimum fresh water flowrate to satisfy the optimal network
FW	m^3/month	Fresh water flowrate
FW_1	m^3/month	Fresh water flowrate of brewery process 1
$FW_{ext.1}$	m^3/month	Fresh water flowrate of external user 1
$FW_{initial}$	m^3/month	Fresh water flowrate of initial network
FW_{new}	m^3/month	Fresh water flowrate for the new designed networks
$\Delta m_{cumulative,j}$	kg/month	Cumulative mass exchanged until the end of mass interval *j*
Δm_i	kg/month	Mass of constituent exchanged in process i
Δm_p	kg/h	Mass of constituent exchanged in process p
m_j	kg/month	Mass of constituent exchanged in interval *j*
N_{int}	[-]	Number of mass intervals
N_o	[-]	Number of processes
WW	m^3/month	Wastewater flowrate
WW_1	m^3/month	Wastewater flowrate of brewery process 1
$WW_{initial}$	m^3/month	Wastewater flowrate of initial network

Glossary

Bright beer	Filtered beer, ready to be packed
Carry over	Caustic that is taken with the bottles from the caustic baths to the water baths
Cast	Result of wort boiling process, also called finished wort
Circularity	The percentage of water from a brewery that can be reused by an external party, after it has been used inside the brewery

Circularity*	The percentage of water from a brewery that can be reused by an external party without treatment, after it has been used inside the brewery
Constituents	The matter in a solution of water and various solutes which are dissolved, colloidal or suspended
Extract loss	Product that is lost during the brewing processes
Grist	Result of grain that has been ground at a gristmill
Influent	The water stream that enters a process
Kieselguhr	Diatomaceous earth, soft siliceous sedimentary rock
Lagering	Process of clarification of young beer where yeast settles in the lagering vessels
Lean stream	Stream with low constituent concentration
Malt	Result of malting process where barley is made to germinate
Mash filter	Filter where the wort and spent grains are separated, also called lautering
Pinch point	The point in a composite curve where the water supply line and composite curve touch
Process effluent	The water stream that leaves a process without treatment
PVPP	*Polyvinylpolypyrrolidone* - Stabilizing agent to adsorb the dissolved polyphenols from the beer to avoid colloidal haze
Reference constituent	The constituent that has the most restrictions in the network design of the water pinch and formed the basis for the integrated network
Regeneration	
Rich stream	Stream with high constituent concentration
Sink	Processes that can receive process effluent from other processes
Source	Processes that provide water to other processes
Spent grains	Residual solid fraction of barley malt remaining after production of wort
Trub	A mixture of water, waste material and hop debris that is separated from the wort in the whirlpool
Water cascading	Creating cascades of water based on purity and flow to target the minimum water flowrate in a network
Water network	A system of processes which receive and provide water supply
Wort	Result of wort production where malt is converted into soluble fermentable sugars and other soluble products
Wort copper	Kettle where wort is boiled and hop is added to obtain the bitterness in beer

1. Introduction

1.1. Context

Water is an important resource in many industries in the world. It is estimated that 22% of the world water availability is used by the industry (Atimtay & Sikdar, 2010). This number will only increase because of the growing population and increasing quality of life. More and more water is necessary to meet the fresh water and product demand. The consequences of this increasing demand is that by 2030, 700 million people worldwide could be expelled by intense water scarcity (Hameeteman, 2013). At the moment, four out of ten people are affected by water scarcity (United Nations, n.d.). Besides, a third of the world's biggest groundwater systems are already distressed (Richey, et al., 2015). In 2015 members of the United Nations adopted the 2030 Agenda for Sustainable Development with 17 Sustainable Development Goals (SDG). Clean water and sanitation with the emphasis on clean water for all is one of the goals, SDG 6. This is one of the most important goals with regard to water scarcity. With the goals set in SDG 6, governments have admitted that they will take action to achieve by 2030 universal and equitable access to safe and affordable drinking water for all and, more importantly, increase water-use efficiency across all sectors to address water scarcity (United Nations, n.d.). The latter has impact on all industries in the world; especially water consuming industries have to be aware of the changing regulations and perspective. Water is not an inexhaustible source anymore and reuse and recycling of water is undoubtedly necessary to keep our planet a liveable place.

Besides the emerging regulatory framework, there are other drivers forcing companies to move towards more sustainable water use. Although water is now a cheap resource, it becomes more and more expensive. Therefore, reducing the water use in an industry results in energy and chemical savings and can reduce effluent discharge fees (wbcsd, 2017). Savings are a big driver for many companies as making profit is the main goal. This is also why reputation is important. The consumer's perspective changes and companies need to show that they are responsible water users otherwise their reputation will be damaged. Reputation damage can result in diminished brand value and decreasing revenues (wbcsd, 2017). Awareness, but also financial support within the company for sustainable water use are the key. In the end, money is necessary to implement sustainable development but profit can only be made if the company production process is sustainable (Davé, 2004).

1.1.1. Solutions to reduce water consumption in the beverage industry

Agriculture, power industry, textile industry, chemical industry, automotive industry, paper industry and the beverage industry are examples of water intensive industries. The beverage industry is among these industries a special one because water is used as ingredient and not only as utility. Water is the main resource and key processing element in the production of beverages. Soft drinks contain 89 – 99% water and beer contains 95% water (Staff, n.d.) (Olajire, 2012). An exception is wine, which also consists of 85% water, but that originates only from the grapes, usually no additional water is added (Miquel, 2016). Besides water as ingredient, water is also used as utility in for example cooling and packaging. Therefore, the beverage industry is highly dependent on the (local) fresh water availability.

In the brewery industry per hectolitre beer approximately 2.9 – 10 hectolitre water is consumed. From this consumed water, 1.9 – 9 hectolitre per hectolitre beer ends up as wastewater (Valta, Kosanovic, Malamis, Moustakas, & Loizidou, 2017) (European Commission, 2006). This amount of wastewater depends on the type of beer, production techniques, size of the brews, how the beer is packaged and age of installation (Olajire, 2012). A brewery uses quite some water and produces at the same time large amounts of wastewater. They have impact on the local watershed and have therefore impact on the water availability in a region.

At the moment, the most common improvement to decrease the brewery's impact on the watershed, is to increase the efficiency of the brewing process. The amount of water consumed per hL beer produced needs to be as low as possible. In 2008, the water consumption was on average 5.0 hL/hL beer in the Heineken breweries and in 2019 it decreased to 3.48 hL/hL. From this 3.48 hL/hL almost 30% is used in the product as ingredient (Heineken N.V., 2015). The process of decreasing the water consumption per hectolitre beer is a process that has developed quickly over time but it has reached almost it surplus. To go from 3.48 hL/hL to 2.5 hL/hL is much more difficult and will cost a lot of investments.

An example of increased efficiency is to use water streams inside a brewery for multiple purposes. The solution is to integrate and connect as much water consuming processes in such a way that the effluent from one process can be used as influent for another process. Feng et al. (2009) developed a new water line in a brewery in China where water is reused in several processes. The new network saved 8% fresh water and there was a reduction of 13% for wastewater (Feng, Huang, Zhang, & Liu, 2009). Tokos et al. (2012) developed a method to optimize the water use and reuse in a brewery with the help of a mixed-integer nonlinear programming (MINLP) model. They showed that integration of sections, and thus exchange of water between sections, can reduce the freshwater consumption undoubtedly (Tokos, Pintaric, Yang, & Kravanja, 2012). These two examples of optimization of the water network in a brewery save fresh water usage in the production of beer. However, they are not solving the problem of the depletion of watersheds. Fresh water is still consumed and wastewater is produced.

A more sustainable approach for breweries is to find solutions that recycle process effluent and/or reuse it for external users. In this way, the water consumption of the brewery is decreased and the local watershed is less affected due to sharing of already extracted water with neighbours. It is common that the process effluents from a brewery are collected as one stream. This is send to an on-site anaerobic-aerobic treatment system from where it is sent to a local municipal wastewater treatment plant (WWTP) before it is discharged into the environment (Jaiyeola & Bwapwa, 2016). This is a situation where it is not clear whether and how much water extracted by the brewery is given back to the same watershed.

A solution could be to treat the wastewater from the brewery more extensively on site from where it can directly be transported to a next user. The next user can use the extracted water from the brewery and does not have to extract water by himself. An example is the treatment of brewery effluent by constructed wetlands. In South Africa this is a proven concept for the reduction of ammonium and phosphate concentrations (Jaiyeola & Bwapwa, 2016). The constructed wetlands produce an effluent with a high enough quality to use as irrigation source for the growth of hydroponic vegetables. Another example is reverse osmosis (RO) treatment to create reusable process water. This treatment requires pre- treatment steps as the RO membranes are very sensitive to fouling. Pre-treatment steps are for example, anaerobic-aerobic treatment and ultra-filtration (UF) (Simate, et al., 2011). Other treatment technologies that can be implemented to produce water for reuse are electrochemical oxidation, membrane bioreactors (MBR) and microbial fuel cell treatment (Vijayaraghavan, Ahmad, & Lesa, 2006) (Dai, Yang, Dong, Ke, & Wang, 2010) (Feng, Wang, Logan, & Lee, 2008). These solutions have one thing in common; they all treat the effluent stream as a combined stream of all the process effluents from the brewery. Lean streams are mixed with rich streams, which means all chemicals and pollutants are in combined in one stream. This creates a situation where several treatment steps are necessary to treat the stream completely before high qualities can be reached. Chemical recovery is in this case difficult as well as reuse by external users.

1.1.2. Water network optimization models

There are different methods for the optimization of water in a network. Most of the techniques establish the minimum fresh water and wastewater targets for water-using processes. Some examples of water optimization techniques are the Water Scan and the Water Cascade Analysis (WCA). Water Scan is a tool that is developed by Royal HaskoningDHV (Royal HaskoningDHV, n.d.). It provides insight in water reuse opportunities and helps closing the water loop in a network. WCA is a tool to obtain quickly minimum fresh water and wastewater targets in a numerical way (Manan, Tan, & Foo, 2004). By creating cascades of water based on purity and flow the minimum water use in the network is calculated. With this information, water networks can be designed where maximum water recovery is established. Both methods originate from the same water optimization method, the pinch analysis.

The pinch analysis was designed as a method to analyse heat exchanges in a network. By identifying energy targets and minimum driving force across heat exchanger's inlet/outlet streams, a network is optimized (Ebrahim & Al-Kawari, 2000). With the so-called composite curve, a graphical representation can be made that specifies the minimum amounts of energy required for every utility in the network. A new design of the network can be constructed with the best heat exchange between hot and cold utilities.

In literature, the pinch method for heat exchange is widely elaborated (Gundersen & Naess, 1990) (Linnhoff, et al., 1982). Examples of the pinch analysis used in energy integration in energy intensive industries can be found in the petroleum industry, chemical industry but also paper and pulp industry (Joe & Rabiu, 2013) (Yoon, Lee, & Park, 2007) (Koufos & Retsina, 2001).

From the 1980s the pinch analysis extension of heat exchanger networks has been developed and other extensions were found (Foo, 2009). It is nowadays used for the design of mass reuse systems, for the reduction of the CO_2 footprint, as a tool for financial planning with money flows and to solve water reuse and recycling problems (Tan, Bandyopadhyay, Foo, & Ng, 2015). The last category, water reuse and water network optimization, is called the water pinch.

The water pinch aims to reduce fresh water usage and wastewater disposal by identifying the water flows and the concentrations of constituents in the streams (Brouckaert, Gianadda, Schneider, Naylor, & Buckley, 2005) (Manan, Wan Alwi, & Ujang, 2006). Where with heat exchange networks the temperature is the only parameter to consider, several constituents influence the network exchanges in a water pinch. This makes the water pinch analysis more complex. Usually a leading water quality constituent is chosen, the reference constituent, to design a water recovery system on. This is the single constituent approach. Examples of such single constituent approach can be found in the sugarcane refinery and brick-manufacturing industry (Balla, Rabah, & Abdallah, 2018) (Skouteris, et al., 2018).

In the water intensive industries it is getting more and more common to use the water pinch method to optimize the water usage and reduce the fresh water consumption. Liang used the water pinch to increase the water savings up to 42.9% in a paper and pulp refinery in China (Liang, 2012). In the coal chemical industry it is implemented successfully to achieve a fresh water intake reduction of 22% (Xiao & Cai, 2017). Moreover, in the ethanol industry Liu et al. showed that with the water pinch the blue water and grey water footprint can significantly be reduced (Liu, Ren, Zhuo, & Fu, 2019).

In the beverage industry a few examples can be found of the water pinch applied to reduce water consumption and increase reuse of effluents. Agana et al. (2013) used successfully the water pinch software to identify possible water reuse opportunities in a soft drink producing plant. In a fruit juice company in South Africa the water pinch saved theoretically 50% of the total water consumption by redirecting streams inside the plant (Brouckaert, Gianadda, Schneider, Naylor, & Buckley, 2005). Although it was not checked if practically feasible, the method showed where the opportunities for improvements were. Thevendiraraja et al. (2003) analysed a citrus plant and showed that by reusing process effluent in the plant, 31% of fresh water consumption could be saved and 31% less wastewater is produced.

In specifically the brewery industry, even less examples of the water pinch are available. One example is of Feng et al. where they used the water pinch to design a new water integration system to reduce the freshwater intake in a brewery (Feng, Huang, Zhang, & Liu, 2009). They selected three groups in their brewery, malting processes, packaging processes and boilers (utility department) to create a composite curve and design a water network. Savings were up to 8% in fresh water consumption and 13% in wastewater production (Feng, Huang, Zhang, & Liu, 2009). Another special example is the research of Zhelev and Zheleva (2002), where they introduced a combination of the water pinch and the original heat pinch. The research focussed on the utilities in a brewery and they tried to show the opportunities of the combined method. However, it became not completely clear how water savings were achieved, it was mainly based on heat exchange.

1.2. Research relevance

In the sections above, multiple solutions are mentioned to reduce the fresh water consumption in the brewery industry. Nevertheless, to solve the actual problem of water scarcity, increasing the efficiency of water use is not the only solution. Two main topics become more important in the water scarcity problem. One is the reduction of wastewater production. The other important solution is to decrease the impact on the watershed by collaboration between water users.

As the solutions of Jaiyeola and Bwapwa (2016) already show; wastewater production can be reduced by reusing effluent inside the brewery. However, most of the researchers focus on end-of-pipe solutions (Feng, Wang, Logan, & Lee, 2008) (Dai, Yang, Dong, Ke, & Wang, 2010). In this case, rich streams mix with lean or even clean streams. Intense cleaning is in this case necessary to reach a high enough quality water to redirect to a process in the brewery. More interesting are solutions that focus on individual process effluents inside the brewery.

For solid waste in a brewery, separation of process effluent is already widely applied. Waste streams inside a brewery such as kieselguhr, spent grains, yeast and broken glass are not mixed but separately collected (Kunze, 1999). These separate waste streams have their own treatment step and next purpose. For water streams, this is not yet so common. This is partly due to a lack of knowledge about the opportunities from the breweries itself but also due to public's perception and distrust of the industries about the quality of the reused water (Simate, et al., 2011). One example can be found in literature of treating process effluent in a brewery. The research of Braeken et al. (2004) focuses on the feasibility of reclaiming brewery wastewaters with nanofiltration (NF). They separated four streams; the effluent after biological treatment, the bottle rinsing effluent, rinsing water of the brew house and rinsing water of the bright beer tank. They showed how these streams could be treated with the NF technology and could be reused in the brewery. This is a good step towards reuse of water in a brewery and thus reducing the production of wastewater. Despite the effort, no other example of reuse of separate brewery effluents could be found. This marks an opportunity to find solutions of reusing process effluent in a brewery.

The other topic is to lower the impact on the watershed by collaboration with other water users in the surroundings. This means expanding the boundaries of reuse to outside the brewery. In other words, increase circularity on water within a local watershed. In literature, few examples could be found of collaborations between a brewery and their neighbours based on water. Jaiyeola and Bwapwa (2016) showed that treated brewery effluent could be used to irrigate land. However, this is combined effluent. No other, relevant examples were found. This knowledge gap can be combined with the lack of knowledge towards reuse of separate process effluents inside a brewery to find a multi-layered solution for the water impact of breweries.

A water optimization model could create the link between the process effluents in a brewery and external users. In this thesis the water pinch is chosen. Several methods originate from the water pinch and it is widely used in literature to optimize water networks. In the majority of the examples from literature, the water pinch is used to optimize the fresh water use and wastewater production in a single industry. This thesis is the first study to use the water pinch in a circularity concept of a wider network with a brewery and external user. By identifying the sources and sinks inside a plant and link the processes to each other an efficient water network inside a brewery and external user could be made.

1.3. Objective and research questions

Based on the literature study and identified knowledge gaps the main research question of this thesis is formulated as follows;

Can the water pinch be used to determine if a brewery in a water stressed area can be 100% circular on water, by reusing process effluent from the brewery by external users?

This research question combines the topics of water scarcity solutions in a brewery with an analytical tool that, so far, has not been used for this purpose. The water pinch is used to optimize water networks insight a single process industry but never in an industry in combination with an external user. This thesis aims to provide an analytical decision making tool to help breweries become part of a circular water network in a local watershed.

To answer this main research question six sub-questions will be answered.

1. *What is the quality of the individual water streams inside a specific brewery?*
2. *What are the influent water characteristics of agricultural external users around the brewery?*
3. *What is the quality gap between the water streams from the brewery and the influent water for external parties?*
4. *Will this method used, to reuse water, cause 100% circularity on water when implemented in a brewery close to their external user?*
5. *Can the water pinch method, as used for the case breweries, be applied to every brewery?*
6. *How can the quality gap be closed between the water streams from the brewery and the desired water quality?*

1.4. Structure of the report

To answer the aforementioned research question and sub questions this thesis facilitates an evaluation of the current situation in breweries followed by an analysis with recommendations. Due to the complexity of data gathering, the analysis is started with a case study of a Heineken brewery in El Obour, Egypt. This brewery serves as an example brewery to test the water pinch. To validate the results a second case study is used of Sharkia, Egypt. First a theoretical background is given in chapter 2 where the concepts circularity and the water pinch are described. In addition, the possible external users around a brewery are highlighted. The chapter finalises with a brief introduction on the beer brewing process including the water use in a brewery. In chapter 3, materials and methods, the steps to complete a water pinch are described. First a description of the case breweries and possible external user is given including their characteristics. This is followed by the description of the water pinch on the case breweries. In section 3.6, the water pinch specific steps were described as well as how to design the actual water networks. Chapter 4, Results, elaborates on the results of the analysis of the El Obour brewery and Sharkia brewery. For the El Obour brewery every detailed step to construct the composite curve and integrated network is given. For Sharkia only the results of the integrated networks are shown. The results are followed by a discussion in chapter 5. This discussion has three parts. First the results obtained in this thesis are discussed including a practical interpretation. The constituent impact on the specific breweries is discussed and solutions to increase the circularity of a brewery are addressed. Second the method used is discussed and in the last part the results are placed in a context of literature. The thesis is finalized in chapter 6 with conclusions and recommendations.

2. Theoretical background

This chapter provides a fundamental background on some relevant concepts. Circularity and possible external users around a brewery are discussed as well as the water pinch. For the water pinch no equations or detailed steps are described. Those can be found in the next sections where the water pinch is applied to the breweries. In addition, some background is given on the beer brewing process and water use in a brewery.

2.1. Circularity

Circularity on its own is actually not a clear defined concept. When searching for the definition of circularity one will find a connection with the word circular, which means as much as:

"S*tarting and finishing at the same place and often following roughly the circumference of an imaginary circle"* (Oxford, n.d.)

Nevertheless, circularity is usually used to refer to the concept of Circular Economy (CE). In many industries, CE is frequently connected with sustainability. The increased pressure to tackle environmental degradation and resource scarcity is a driver to search for new solutions. Circular economy is considered as the solution that combines economic growth and environmental protection (Lieder & Rashid, 2016). Geissdoerfer et al. (2017) supports this environmental perspective of CE and defines the concept as follows:

"Circular economy is defined as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling." (Geissdoerfer, Savaget, Bocken, & Hultink, 2017)

Even as Geissdoerfer et al. (2017), the Dutch Ministry of Infrastructure and Environment's (2015) definition of CE, is based on the definition of the Ellen MacArthur foundation. The definition of the Ellen MacArthur foundation is accounted for as the most renowned definition for CE and reads:

"[CE] an industrial system that is restorative or regenerative by intention and design. A circular economy aims to decouple economic growth from the consumption of finite resources and build economic, natural, and social capital. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models." (Ellen MacArthur Foundation, 2019)

But that CE is a concept that has a wide range of definitions provided by several organisations, academics and governments, is shown by Kirchherr et al. (2017). In their research, 114 definitions of circular economy were analysed. They tried to discover what the current understandings are regarding CE. They found out that circular economy is frequently described as a combination of reduce, reuse and recycle activities (Kirchherr, Reike, & Hekkert, 2017). They came to the following definition:

"[CE] an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations."

This definition harmonize the environmental aspects with the economic importance that is described by Lieder and Rashid (2016) as a fundament for CE. This definition of CE covers a range of possible perspectives; there is CE on materials, resources, energy, biodiversity and water. To go back to the concept of circularity, one could say that a CE is composed of circularity on all those different aspects as water, energy and materials. For the scope of this research, only water is considered. Thus, when a brewery is circular on water, the brewery contributes to a circular economy. The exact definition that is used for circularity in this thesis reads therefore:

"Circularity is the percentage of water from a brewery that can be reused by an external party, after it has been used inside the brewery."

Circular on water and circularity are used interchangeable.

2.2. External users in the surroundings of a brewery

In the main research question of the thesis the 'external user' of a brewery is mentioned. Based on the location of the brewery, all kinds of external users could be present. For example paper mills, automotive industry, wood industry and agriculture could be possible users of the same watershed a brewery is extracting from. In this research the focus will be on agricultural external users. There are three reasons for this.

The first one is that agriculture is the largest consumer of fresh water globally. 70% of the total fresh water consumption is used in the agricultural industry (UNESCO). They have an effect on the lakes, rivers and groundwater aquifers. As stated by the FAO, agriculture is both a victim as well as the cause for water scarcity (FAO, 2016). Due to the increasing demand for food by the increasing population, the agriculture business grew exponentially without taking care of the effects on fresh water availability. Especially due to inefficient irrigation and land use, aquifers depleted. Inefficient management with extensive use of fertilizers and pesticides is causing water pollution in the sources of irrigation. This creates a loop where water becomes scarcer due to overusing and the water that is still left is at the same time polluted, making fresh water even scarcer.

The second reason is climate change. Climate change affects the agricultural industry. It causes problems with water availability for agriculture. In temperate zones the precipitation will increase with higher chances of extreme weather causing damage to crops and land (FAO, 2016). At the same time, in semi-arid regions where draught is already an issue, less precipitation will occur. Especially the last group is vulnerable to the decreasing fresh water availability (FAO, 2016).

Another simple reason is that most water stressed breweries are located in countries where agriculture is one of the main occupations.

Important parameters for agricultural users in general are salinity, especially sodium and chloride ions, phosphorus and nitrogen. Salinity is one of the most important constituents that forms a threat to agriculture. The salt ions have a toxic effect on crops and soil when present in high concentrations. The yield of crops decreases significantly with higher salt content and with the increased salinization of the ground, less ground is available for agriculture (de Vos, et al., 2016). Sodium and chloride ions are the main salt ions causing salinization.

Phosphorus and nitrogen are parameters added to the irrigation water because they have a positive effect on the growth yield of crops. Phosphorus is essential for the growth because it stimulates the plant metabolism, structure and life (Day & Ludeke, 1993). Nitrogen is the other essential for plant growth as it plays a role in the protein production of plants. It increases the growth yield and uptake of other nutrients as phosphate (Leghari, et al., 2016). That is why most fertilizers contain a form of nitrogen in combination with phosphorus. Both play a vital role and it is beneficial for the crop yield to have phosphorus and nitrogen in the irrigation water. However, it may happen that a wastewater contains an excess of nutrients. In this case, growth of other vegetative is possible and weed problems can occur with more maintenance as a result (Kang, Kim, Park, Lee, & Yoo, 2007). This should be examined more intensively but this is out of the scope of this research.

2.3. Water pinch

As said in the introduction, the water pinch is a method to optimize the water usage in a network. It is developed to target the minimum fresh water flowrate and reduce wastewater production. By identification of water streams and their characteristics, new networks can be designed based on reuse possibilities. In short, the water pinch works as follows: per water-using process the water flowrate and constituent concentration(s) are determined. For every process the transferred mass of the constituent is calculated and determines whether the process can receive or provide water. For small networks with a limited amount of processes, identification of water reuse opportunities might be easy and a full water pinch is perhaps not even necessary. However, the more complex a network becomes, the harder it is to determine every possible mass-exchange alternative.

For this reason the composite curve was developed; to give a quick, graphical output. El-Halwagi and Manousiousthakis introduced the limiting composite curve in 1989. Based on the heat exchanger network model of Linnhoff and Hindmarsh (1983), they developed an approach applicable to mass exchange networks. The composite curve is a tool to indicate the mass exchange between rich and lean streams in a network by modelling them as a single using process. They applied their approach to a water network and this was how the water pinch was developed. In the composite curve graph the fresh water supply line is added to determine the pinch point. The pinch point is the constituent concentration where the fresh water flowrate is at a maximum level and indicates the limiting reuse concentration. The composite curve in combination with the water supply line forms the basis for an optimized network design. There are two different ways of targeting the minimum water flowrate in a network with the water pinch and composite curve: the fixed load problem and the fixed flowrate problem. For a more detailed explanation of the construction of the composite curve, see examples in section 4.5.

2.3.1. Fixed load problem

The fixed load problem approach focuses on the mass transfer-based water-using processes (Foo, 2009). In a network, water is used as separating agent to clean rich streams. Every stream has its impurity load and the goal is to use the water (fresh or from low contaminated processes) to remove the impurity load of the rich streams. The water flowrate is of secondary concern. A low contaminated, lean process effluent can be used at different constituent concentrations to dilute rich processes. An example can be found in Table 1 from Wang and Smith (1994). Four processes with a fixed mass load, in- and outlet constituent concentration and a certain flowrate are shown in Table 1. With this data, a composite curve is constructed with a pinch point at constituent concentration of 100 mg/L, see Figure 1.

Table 1: Data for water pinch example with fixed load problem with four processes (Wang & Smith, 1994)

Process	**Δm_p [kg/h]**	**C_{in} [mg/L]**	**C_{out} [mg/L]**	**f_p [m^3/h]**
1	2	0	100	20
2	5	50	100	100
3	30	50	800	40
4	4	400	800	10

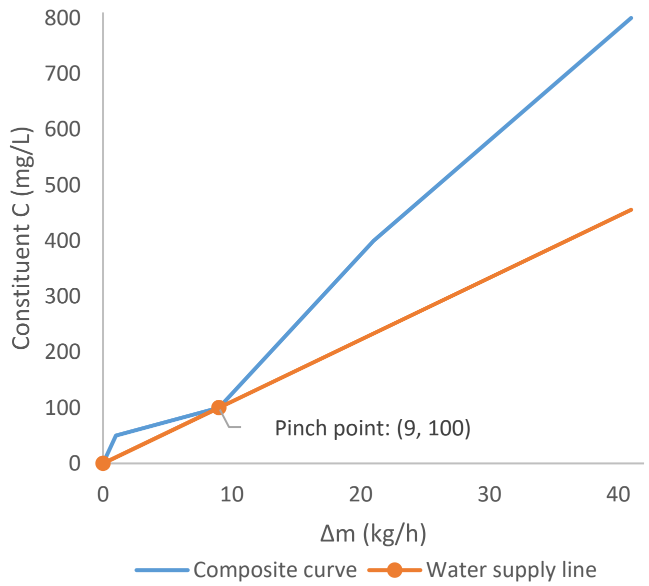

Figure 1: Composite curve for example fixed load problem from Table 1

The minimum fresh water flowrate required to satisfy this network is 90 m^3/h. Figure 2 shows the network designed for this fixed load problem. Although process 1 requires only 20 m^3/h, all the fresh water enters via this process the network to pick up the first impurities. When the stream reaches a constituent concentration of 50 mg/L the stream is separated into three streams to supply process 2, 3 and the remaining to process 1. When the outlet streams of these processes have reached a constituent concentration of 100 mg/L, the water is sent to solely process 3, and so on. This way of targeting the minimum water flowrate in a network suggests that within a process, different stages of impurity concentration exist and can be intercepted.

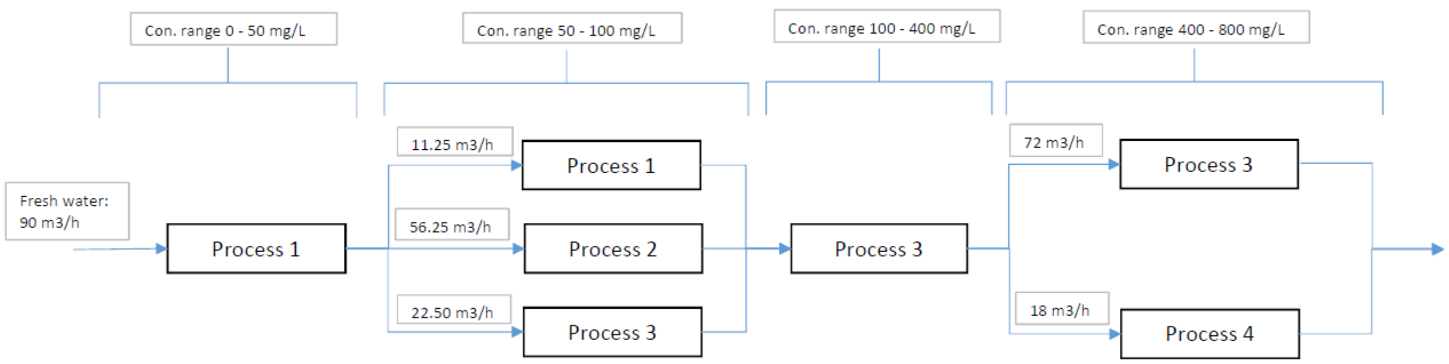

Figure 2: Stream population within the limiting composite curve example fixed mass load problem from (Wang & Smith, 1994)

2.3.2. Fixed flowrate problem

Sometimes the flowrate of a stream is more important. Therefore, another way of targeting was developed, the fixed flowrate problem (Foo, 2009). In this method, the water flowrate is the main constraint and not the impurity load. Processes are defined as sinks or sources. The network is designed in a way that sources satisfy sinks based on fixed flowrates. Depending on the effluent concentration of a source and influent concentration of a sink, connections are made. The requirement is that a process is always satisfied with its specific water flowrate.

In Table 2 an example is shown of data from a network with a fixed flowrate. There are four process with for every process a fixed flowrate, maximum in- and effluent concentration. Due to the fixed flowrate, the water in the network can only be used at the maximum influent and effluent concentrations of the processes. No interception of water during the contamination of a stream is possible. However, dilution of rich streams with lean streams is possible.

Table 2: Data for example water pinch with fixed flowrate problem (Wang & Smith, 1994)

Process	***f_p* [m³/h]**	***C_{in}* [mg/L]**	***C_{out}* [mg/L]**
1	20	0	100
2	100	50	150
3	40	50	600
4	50	400	800

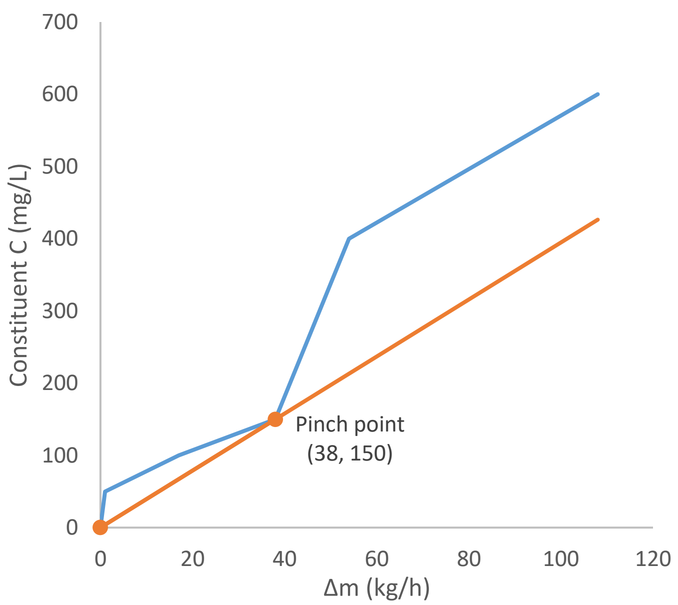

Figure 3: Composite curve for example fixed flowrate problem with data from Table 2

The composite curve for the fixed flowrate problem example from Table 2 is shown in Figure 3. The pinch point is located at a constituent concentration of 150 mg/L. This means that the processes with a $C_{out} > C_{pinch\,=\,150\,mg/L}$ are identified as sinks and process with $C_{out} < C_{pinch\,=\,150\,mg/L}$ are identified as sources. Two sources, process 1 and 2, and two sinks, process 3 and 4, could be identified. Figure 4 shows the network design for the fixed flowrate problem from Table 2. For this network 140 m^3/h fresh water is required instead of 210 m^3/h in the initial network. The flowrates of the sources were sent to the sinks that have a $C_{sink,\,in} \geq C_{source,\,out}$. The required sink flowrate is completely satisfied by one or multiple sources, depending on the flowrate available per source. Fresh water can be used to dilute rich streams. This is shown for the effluent of process 1, this stream is diluted with 20 m^3/h fresh water to satisfy process 3. Different from the network for the fixed load problem, a single source is not used at different concentration levels to satisfy a sink.

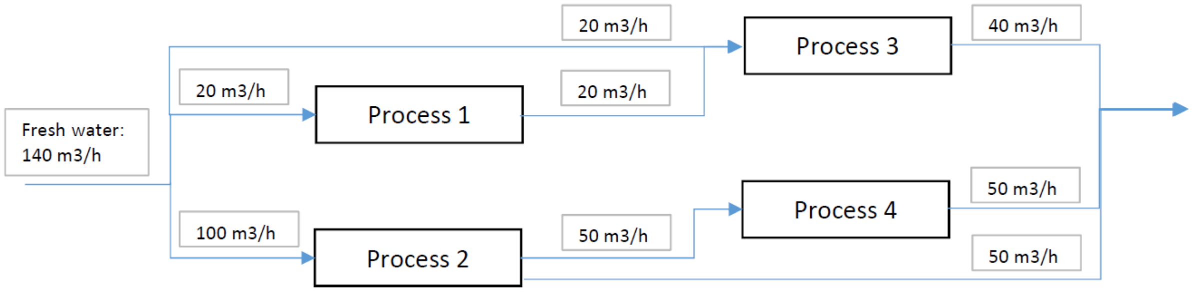

Figure 4: Network design for example fixed flowrate problem from data Table 2

Nowadays the fixed flowrate problem approach is used for most of the problems. This is because mass transfer water-using processes are more complicated when the network increases (Foo, 2009). The source-sink approach in the fixed flowrate problems are less complex and more easily implemented. In this research the fixed flowrate problem approach is used.

2.4. Brief introduction of the beer brewing process

In this section, the beer brewing process is briefly described to give a general overview. Figure 5 shows the flow diagram of the beer brewing process from malt until bright beer. A brewery consist usually of roughly four parts; a brew house, cellars, a packaging area and utilities. The packaging area and utilities are separate areas and are discussed later on in this thesis in the section of identification of water in the brewery.

The brew house is the phase in the production of beer where malt is processed into wort. Malt, calcium, some acid and water are mixed in the mashing vessel from where it continues through the mash filter, wort buffer tank, holding vessel to the wort copper. Here, some extra hop extract and calcium chloride could be added to enhance the process. In the wort copper the mixture is boiled. The steam that is generated is collected in a pipeline and cooled to condensate. The condensate is send back to the beginning of the brew house (Berkhuizen, 2019). The last process in the brew house is the separation of the wort and trub, and cooling of the wort. The clear wort is then ready for the fermentation phase. This trub is a mixture of water, waste material and hop debris that is collected together with kieselguhr waste from the kieselguhr filter to be used as animal feed.

Clear, cooled wort is flowing from the brew house into the cellars. This is the part where the fermentation takes place and the bright beer is produced. Yeast is added in the horizontal fermentation tank (HORAP) tank and simultaneously the wort is aerated to start the fermentation. The fermentation process continues in the fermentation/storage tanks (FST cellars) where also some product water is added. Young beer is the product that remains after fermentation. Yeast that is left in the vessels is returned to the yeast storage tank to be reused. The young beer is stored in the unfiltered beer tanks and some stabilizing agents are added. The stabilizing agents are added to delay the formation of colloidal haze, especially necessary when beer is stored for a longer period. The main stabilizing agents are polyvinylpolypyrrolidone (PVPP) and kieselguhr, both can be used together. The mixture is filtered in a kieselguhr filter to create filtered beer. The filtered residue is the kieselguhr waste and this is used with the trub as animal feed. CO_2 is added to the filtered beer to create the final product, bright beer. The bright beer tank is the last stage of the cellars before the beer is going to the packaging area. In the packaging area the beer is packed in bottles, cans, kegs or PET bottles from where it is sent to the customers.

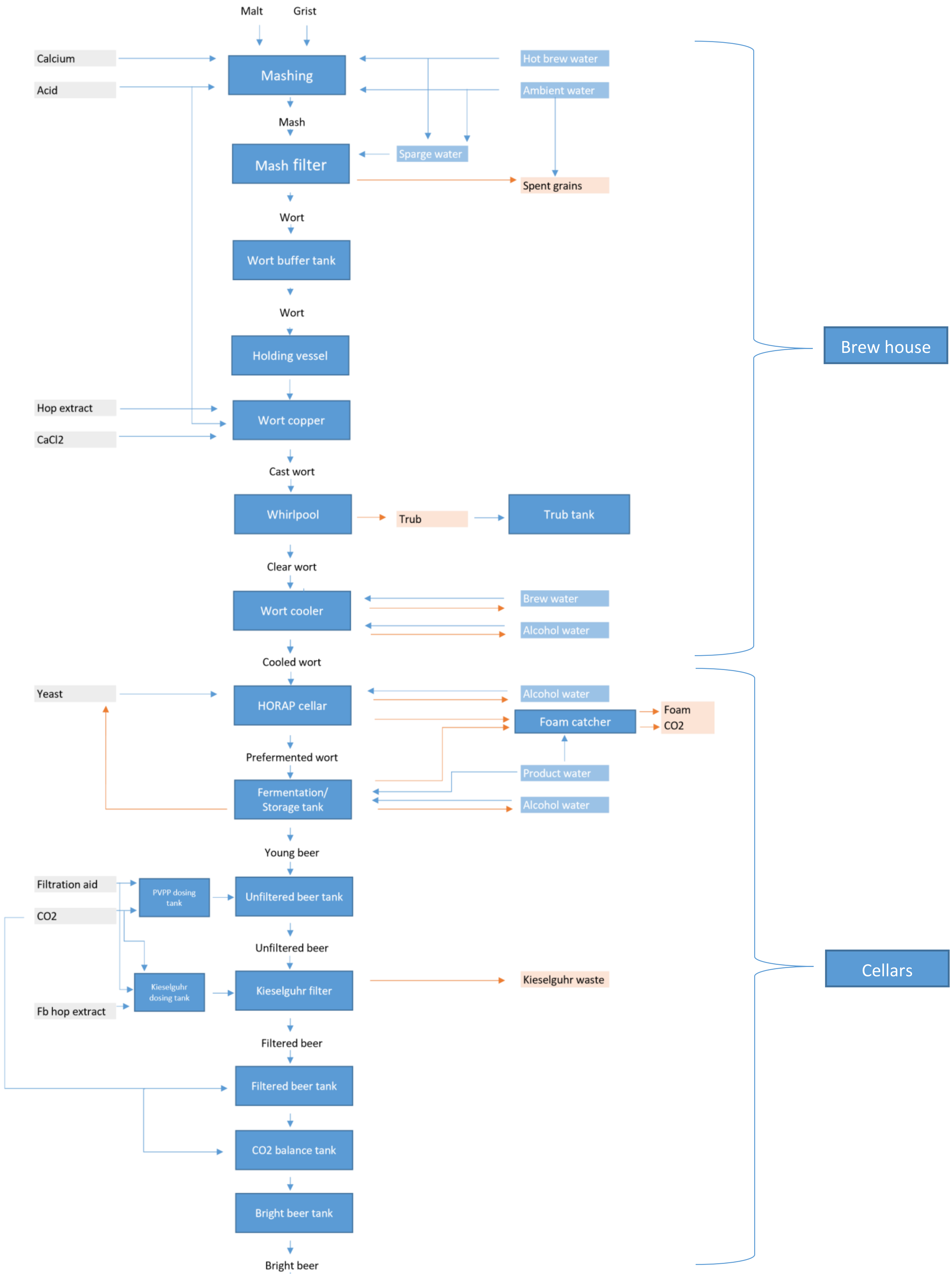

Figure 5: Flow diagram of general beer brewing process. Blue lines indicate influent streams and orange lines indicate effluent streams.

2.5. Water use in a brewery

As said before, the brewery consists of four parts, the brew house, cellars, packaging area and utilities. As shown in Figure 5, during the beer brewing processes water is only used as ingredient. However, water is also used for cleaning and utility purposes. In this section the water types that could be found in a brewery were described.

2.5.1. Water as ingredient

The first category is water used as an ingredient for the final product, namely the beer itself. Beer consists of 95% of water, making it the main ingredient of beer. The water that ends up in the beer is consumed water and does not generate a wastewater stream. As Figure 5 shows, water is added in the mashing stage and stays inline until the bright beer tanks where it is transformed into beer. As stated in the introduction section, 2.9 – 10 hL water per hL beer is used and 1.9 – 9 hL wastewater per hL beer is produced (Valta, Kosanovic, Malamis, Moustakas, & Loizidou, 2017) (European Commission, 2006). This means that around 1.0 hL water is used as ingredient per hL beer. This water cannot be used in a circularity problem as it is consumed. Therefore, the group, water as ingredient in the brewing production, is not taken into account in the water pinch. Processes that only use water as ingredient were excluded (brew house and cellars processes, see Figure 5).

2.5.2. Water as utility

The second purpose of water in a brewery is water used as utility. As said above, 1 hL water ends up in the beer itself and 1.9 – 9 hL is used elsewhere. This water is water used as utility. There are three main categories where water is used as utility; the CIP processes, in the packaging department and in the utility department.

Cleaning in place

The main purpose of water used as utility in the brewery, is cleaning. Every vessel, pipeline and storage tank needs cleaning after use. Because the brewing process is a batch process, cleaning is a regularity. After every batch the whole line is cleaned before a new batch is started. Water during cleaning is used for rinsing, pushing out remaining product and as solution for cleaning additives.

Within Heineken there are standard procedures for cleaning in place, although every brewery has their own way of cleaning based on the standards. Depending on the number of tanks and location, every block or building has its own CIP installation. The CIP installation usually consists of an acid tank, caustic tank and a recirculation/water tank. Pipes from a buffer tank on the brewery location supply product water. Although every building has its own CIP installation the water used for cleaning purposes can also be divided in three parts.

The first part where water is used for cleaning is in the brew house, mashing vessels until whirlpool, (see Figure 5). In this part of the brewery, water is used as rinsing water and as part of the cleaning solution with caustic; no disinfectant or acids are involved. From separate tanks hot water and hot caustic solution are sent through the process line. After every cleaning step the solution or water is pushed out and sent to the drain where it is transported to the wastewater treatment (WWT) facility. Table 3 shows a regular cleaning procedure of the tanks in the brew house. Exceptions in the brew house were the wort copper and wort cooler CIP. These tanks have their own CIP procedure. This is because especially in the wort cooler, wort rests can stay in the tank and good cleaning is required.

Table 3: Standard cleaning and disinfection procedure brew house (Heineken Global Supply Chain, 2015)

Steps	Objective
Drain vessels, accessories and connecting pipework	Remove residual liquids
Hot caustic circulation	Removal organic compounds, cleaning, sanitation/disinfection
Hot caustic rinse of connecting line	Line cleaning
Fresh hot water rinse	Removal caustic rests, rinsing
Fresh hot water rinse of connecting line	Line flushing

The second part where water is used for cleaning purposes is in the brewing processes of the HORAP cellar until bright beer tanks; the cellars. Here the cleaning procedure is more extensive and besides a hot water and hot caustic solution, acid, disinfectant, cold caustic and cold fresh water are used. The cleaning procedures determine how much caustic, acid or disinfectant end up in the effluent that is going to the WWTP. Table 4 shows a regular cleaning procedure of the cellars tanks. Important to mention is that not every step is directly going to the drain because recirculation is applied. In the case study exact values were obtained to determine how much CIP water goes to the drain. A special case in the cellars is the water use for the air removal in the Beer Membrane filter (BMF) and PVPP tank. This is only the case when a BMF is used instead of a kieselguhr filter.

Table 4: Standard cleaning and disinfection procedure cellars (Heineken Global Supply Chain, 2015)

Steps	Objective
Water rinse	Removal of yeast rests[1]
Fresh caustic pulses	Removal resin scum, penetration 'brandhefe'
Water rinse	Removal caustic rests
Acid and disinfection circulation	Removal of scale formers and disinfection[2]
Fresh water rinse	Removal disinfection/detergent resins

Packaging department

The next department where water is used as utility is in the packaging area. This is a separate part of the brewery where the beer from the bright beer tanks is packed in bottles, kegs and cans. In this part no water is added to the final product, water is only used as an utility. This means that all water used in this department ends up as wastewater.

In Figure 6 a general packaging line for returnable bottles (RB line) is shown. In this figure, the processes using water are highlighted with yellow lines. The majority of water is used for cleaning purposes in the crate washer, bottle washer and filler but it is also used in the pasteurizer as heat exchanger and rinser. In the packaging area the bottle washer has its own caustic and fresh water tanks. The filler and the pasteurizer use fresh water tapped from fresh water storage tanks, usually

[1] Only HORAP, Yeast storage tanks, yeast propagation tanks, yeast re-hydrator

[2] This step is sometimes divided in a separate acid and water rinse followed by a separate disinfection and water rinse, depending on the type of tanks and local procedures

outside the packaging area. The water that is used with cleaning, filling and pasteurizing the bottles, ends up as process effluent and is send to the WWTP.

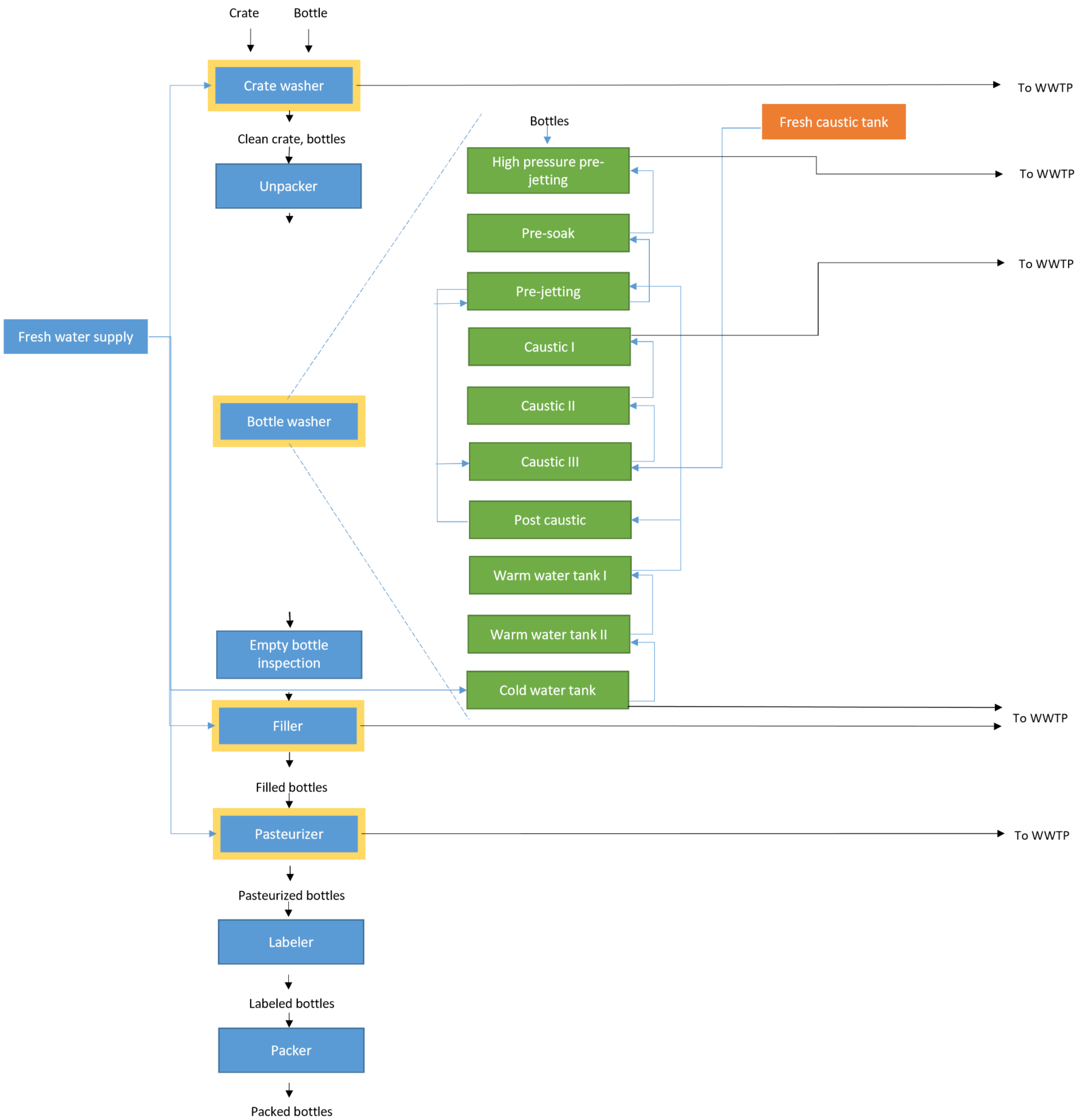

Figure 6: Returnable bottle line flow diagram. Yellow lines indicate water-using processes. Blue arrows represent influent streams to the processes. Black lines represent the effluent streams to the WWTP.

The flows and processes in the returnable bottle line are similar to the one way bottle line (OW), can and keg line. Figure 7, Figure 8 and Figure 9 display a general OW bottle line, can line and keg line with yellow highlighted areas where the water is used and process effluent is produced. OW bottles can be made of glass or PET. Like the RB line; the OW bottle rinser, OW bottle filler, OW bottle pasteurizer, can rinser, can pasteurizer, keg washer and keg pasteurizer produce a process effluent. The keg washer is similar to the bottle washer as it has a rinsing with water and caustic. But different from the bottle washer it is followed by an acid bath or second caustic bath. The can line is more simple because there exists no returnable cans. New cans are relatively clean and rinsing with clean water is enough before filling. Different from the bottle and keg filler, the can filler doesn't use water. This is because cans have a low resistance to a vacuum and are very fragile. Therefore the filling is done by purging CO_2 in the can to counter pressurize it from where the can is safely filled with beer (Kunze, 1999).

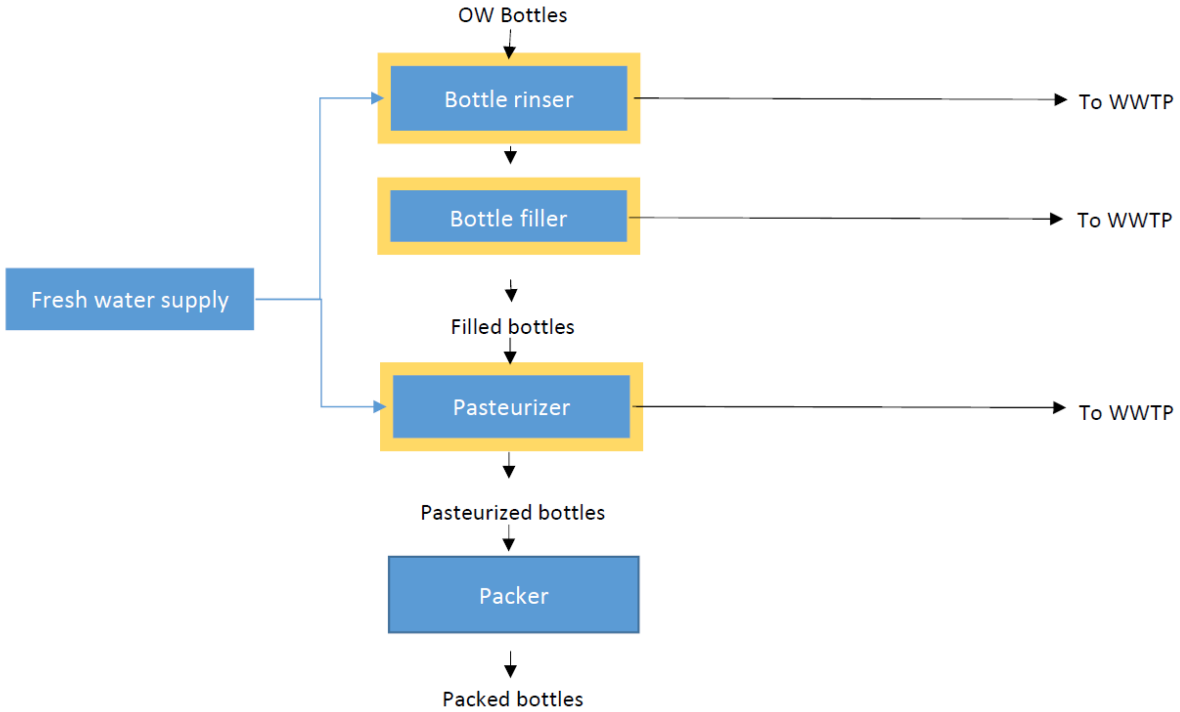

Figure 7: One-way bottle line flow diagram. Yellow lines indicate water-using processes. Blue arrows represent influent streams to the processes. Black lines represent the effluent streams to the WWTP.

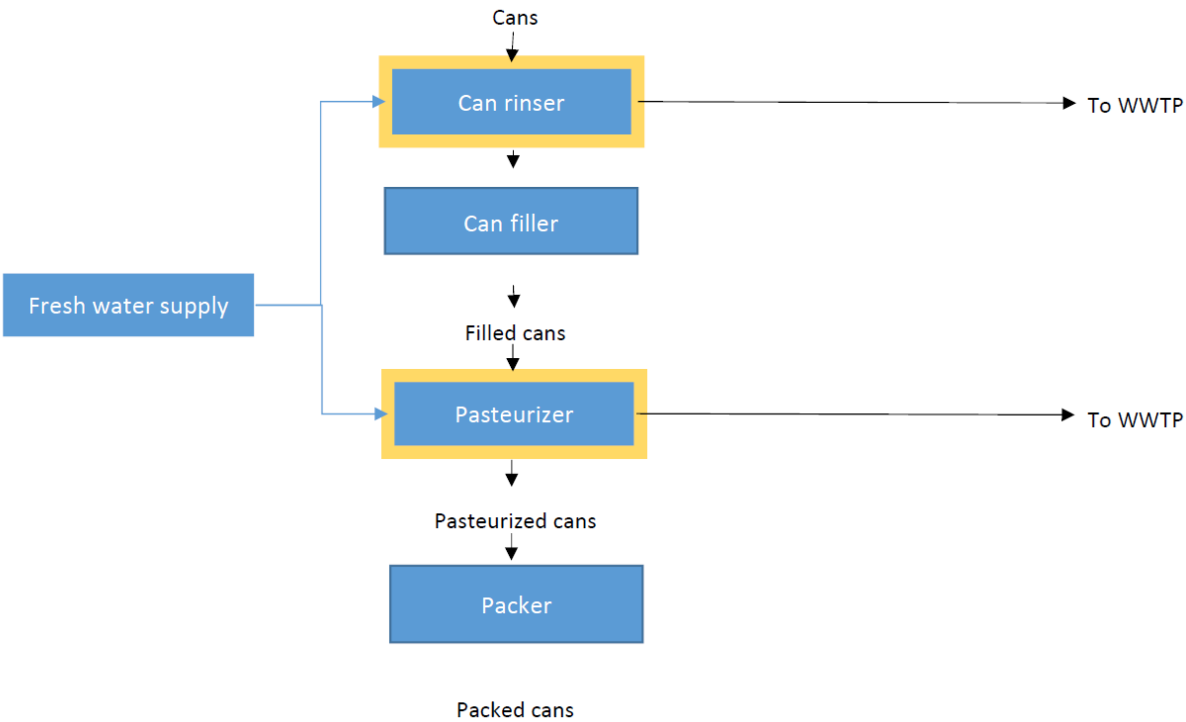

Figure 8: Can line flow diagram. Yellow lines indicate water-using processes. Blue arrows represent influent streams to the processes. Black lines represent the effluent streams to the WWTP.

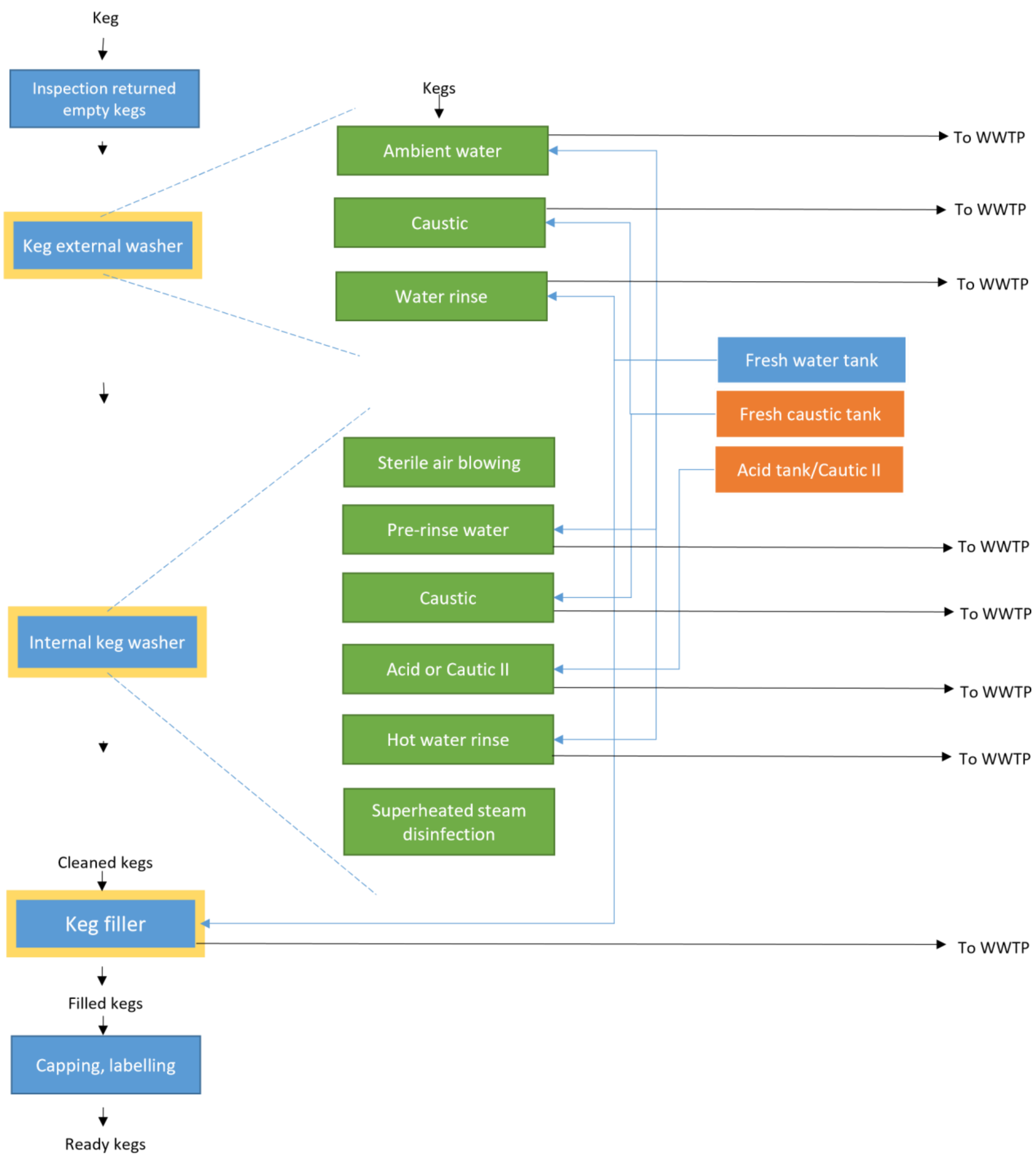

Figure 9: Keg line flow diagram. Yellow lines indicate water-using processes. Blue arrows represent influent streams to the processes. Black lines represent the effluent streams to the WWTP.

Utilities

The last place where water is used as utility is in the utility department. The utility department contains the boilers, CO_2 washers, cooling towers and water- and wastewater treatment plant. All these processes do something with the water involved in the brewing process such as, boiling, making steam, cooling and treating but they also consume some water during these processes. Boilers create steam for pasteurizing and sanitizing bottles and kegs. With the mechanism of steam making the water in the boiler should be replaced from time to time to avoid steam contamination. The replaced water is called the blowdown water and that could be considered as a process effluent in the utility department. The blowdown rate ranges from 4 – 8 % of the boiler feed water, depending on the solid content and boiler type (Advanced Manufacturing Office, 2012).

Cooling towers provide the water that is used for cooling the beer in, for example, the wort cooler and after the fermentation tanks. This is usually a recirculation flow and the cooling water does not come in contact with the beer or other streams, it only takes up the heat. In a cooling tower replacing of water is needed to remove the water with high mineral concentration. The mineral concentration is due to scaling that originates from the evaporation of water. This water is the blowdown water of the cooling tower and is a process effluent in a brewery.

In the CO_2 washer, water is used to wash the CO_2 gas flowing from the cellars by removing ethanol, acetaldehyde and tiny particles (Kunze, 1999). This water is flowing downward while the gas is flowing upward. The water is collected afterwards and send to the drain. This is another process effluent in the utility department.

The water and wastewater treatment plant is out of the scope of this report because the purpose of this research is to look at separate process water flows after the water treatment plant and before the WWTP.

2.5.3. Water types in a brewery

There are three types of water used in the beer production processes, listed below. The quality requirements are based on information of Heineken (Heineken Supply Chain B.V., 2016).

- Product water. Product water is water that is used as a basis for soft water production but is also used in some CIP or other general purposes. The product water is obtained from treated well or surface water. The required quality for every water in the brewery is the same as drinking water standards set by the local government of a brewery or the World Health Organisation (WHO) (whichever is more stringent) with some extra requirements. The extra requirements for product water are shown in Table 5.
- Soft water. Soft water is the water that is used for CIP. Product water is treated with an ion exchanger and calcium carbonate to produce soft water. The extra quality requirements are listed in Table 5.
- Brew water. This water is used as ingredient for beer. It is used in the mash filter as sparge water, as ambient water in mashing stage but also sometimes as cooling water. Brew water is used in the processes where beer is involved. It has the strictest quality requirements as it comes in contact with the final product or is part of the final product. The extra quality requirements on top of the WHO drinking water requirements, are shown in Table 5.

Table 5: Additional quality requirements product, soft and brew water in addition to the WHO drinking water quality guidelines (Heineken Supply Chain B.V. 2016)

	Quality requirement		
Parameter	***Product water***	***Soft water***	***Brew water***
Chloride	< 30 mg/L	< 30 mg/L	< 30 mg/L
THM's	<100 µg/L	<100 µg/L	<100 µg/L
Chlorite	< 0.7 mg/L	< 0.7 mg/L	< 0.7 mg/L
Chlorate (ClO_3^-)	< 0.7 mg/L	< 0.7 mg/L	< 0.7 mg/L
Total Hardness	-	≤ 2˚G	≤ 15˚G
LSI (Langelier Saturation Index)	-	-0.5 ≤ LSI ≤ + 0.5	-1.0 ≤ LSI ≤ + 0.5
Residual disinfection power by free chlorine/ClO_2	-	< 0.5 mg/L	< 0.1 mg/L / < 0.1 mg/L
Calcium	-	-	< 100 mg/L
Magnesium	-	-	< 20 mg/
Silicate	-	-	< 50 mg/
Evaporation residue	-	-	< 1000 mg/L
pH range	-	-	6.5-7.2

2.5.4. Constituents in the process effluent of a brewery

Based on the quality characteristics of the water used in the brewery, important constituents that are relevant for reuse can be determined. For the four departments an identification of the possible constituents is given in this section.

Brew house and cellars constituents

The water used in the brew house and the cellars for CIP is brewing water, product water and soft water for the caustic solution. Additives to these streams in the brewing part could be caustic, acid and disinfectant. Caustic is in this case sodium hydroxide and the main acids are phosphoric acid and sulphuric acid. The disinfectants used contain usually chlorite ions. All these additives end up in the process effluent of the CIP brew house and cellars.

Besides the additives during cleaning that changes the quality of the process effluent, the last product left in the vessels play a role as well in the brew house and cellars. The first cleaning step is always a push out or rinse out of the product that is still left in the tanks and pipelines. This last product, the extract loss, is important for a brewery to know to have an idea of how much product is lost during production. The characteristics of the extract loss are determined by identifying the ingredients of beer. Beer is made out of four ingredients, water, grains, hop and yeast. By processes as fermentation, lagering and filtering, it becomes beer. During these processes co-products are formed, such as sugars, alcohol, amino acids and peptones (Kunze, 1999). Besides, in the mashing stage some calcium and acids are added and in the wort copper some extra $CaCl_2$. The co-products and additives can all end up in the effluent of the processes, as they will stick to the wall of the tanks or stay in the tank with some final product.

These constituents cause high CODs as the extract loss and ingredients of beer consists of organics. Especially the yeast in the HORAP and FST cellars cause high CODs in the solutions of the tanks. The final product stream consists of brew water with residues of yeast and other organics and ranges from 40 mg COD/L until 200 000 mg COD/L.

Due to the formation of protein breakdown products during malting and brewing the ammonium concentration is increased. The amino acids, peptides and peptones will increase the total N content of the process effluent.

Packaging department constituents

For the packaging department caustic is added to soft water. This causes high concentrations of sodium hydroxide in the process effluents. Sodium is therefore indicated as an important constituent for the packaging department. The main water-using processes in the packaging department are the returnable bottle washer, crate washer and keg washer. Especially the returnable bottles can contain high concentrations of microorganisms, organic compounds, glue of the labels, the labels itself and other filthiness. The effluent of the pre-soak bath is therefore highly contaminated. COD is a good indicator for this effluent. Other sources for COD in the packaging area are the extract losses in the filler and breakage of bottles or other packaging material in the pasteurizer after filling.

Utility department constituents

In the utility department, the influent for all processes is product water. Inside the boiler the water is contaminated with small particles of dust or other residuals that were present in the pipes. Besides those, no other constituents than COD or salts should be there. The blowdown water from the cooling tower can be contaminated with minerals that were formed during the evaporation of water, corrosion inhibitors or biocides. The CO_2 wash water is contaminated with tiny particles from the gas and can contain ethanol, acetaldehyde, and ethyl acetate (Nigerian Breweries Plc, 2013). These streams are relatively clean and have low to zero COD, sodium or Total N concentration.

3. Materials and methods

The water pinch is used to identify to what extend a brewery can be circular on water. Circularity is defined as the amount of water from the brewery going to the external user, see section 2.1. This can be with regeneration of the stream or without. However, in this thesis first the possibilities of reuse of brewery water without treatment were investigated. This resulted in an initial reuse percentage of the brewery. Circularity in this section is defined as Circularity* and reads;

"Circularity is the percentage of water from a brewery that can be reused by an external party, without regeneration, after it has been used inside the brewery."*

In the discussion, section 5.1.4, solutions were addressed to increase the overall circularity which means that regeneration of streams are allowed. In this report one case study is used to elaborate on the water pinch and how to apply it. However, to validate the principle of the water pinch in combination with the concept of circularity, another case brewery was used. Both breweries were modelled at actual process water flowrate values as well as on optimal process water flowrates. The latter one is called the Utility Bench Mark (UBM) values. Heineken determined for every brewery the best practise values for electrical energy, thermal energy and water consumption based on local and regional conditions. These values serve as a goal for breweries to reach optimal conditions and thus produce beer in the most efficient way possible. Therefore, it is interesting to apply the water pinch with UBM process water flowrate values to compare the outcome of the analysis with the actual process water flowrate results.

With the help of the researches mentioned in 1.1.2., a step-by-step instruction was composed to apply the water pinch on a brewery and create a new design for the brewery water network. Point 1 through 13 below show briefly the steps that were followed. Between brackets the sections in this chapter where the step is described in detail, were shown.

1) Analyse the location of the brewery and identify possible external user(s) *(section 3.1)*
2) Determine influent characteristics of the external user(s) *(section 3.1)*
3) Determine the water-using network in the brewery *(section 3.2)*
4) Undertake a pre-screening of the water used in the brewery to define the key processes and key constituents *(section 3.2, 3.3, 3.4)*
5) Simplify the water network to exclude processes that do not offer any scope *(section 3.3)*
6) Collect quantitative data of water flow and key constituent concentration for the key processes. *(section 3.5)*
7) Determine the maximum allowable in- and outflow concentrations of the constituents. *(section 3.5)*
8) Construct, per constituent, the composite curve with the water pinch formulas *(section 3.6)*
9) Determine the optimal design assuming current operation conditions are limiting *(section 3.7)*
10) Choose the reference constituent based on the required maximum fresh water flowrate calculated per network. Use this network as the base network. *(section 3.8)*
11) Check if the redirections made in the network of the reference constituent comply to the other constituent requirements, if not change the network *(section 3.8)*
12) When the reference constituent network is adapted to every requirement the integrated network is composed satisfying all constituent restrictions *(section 3.8)*
13) Return to step 5) if there are changed constraints and outlet conditions *(section 3.8)*

3.1. Identification possible external users around the Heineken brewery

In this section, the possible external users of process effluents from the brewery were identified. The focus in this report for external users is on agricultural external users. For the case breweries one external, agricultural user is chosen. Irrigation water quality requirements were used as a guidance to determine if the water from a brewery can be reused. There is several research done towards the impact of irrigation water from wastewater. Based on these researches the influent limits for the agricultural user were determined. The strictest limit is taken to ensure that there will be no problems with the crops. One assumption made is that the water that is irrigated, is irrigated directly on the ground. This means that no sprinklers are used only surface irrigation methods. Sprinklers can increase the toxic effect of toxic ions because leaves can also take up ions directly. This reduces the sodium, chloride and other ions concentration limits (Ayers & Westcot, 1985).

Based on the information from literature, a list of important quality constituents was made for the external user. Also the impact of the critical constituents was highlighted.

3.2. Key processes in the Heineken breweries

Before the actual water pinch could be applied, the water network of the brewery had to be identified to scope the area of interest. Not every process inside the brewery is relevant as the water pinch focuses on water. Processes without water or without wastewater production are therefore irrelevant and had to be excluded from the selection. As said in section 2.4 the brewery consists of roughly four departments, a brew house, cellars, a packaging department and utilities. In these four parts water is used as an ingredient as well as utility (see section 2.5). Based on this identification of water usage in a brewery the key processes were determined. The criteria for selecting a key process is;

- A key process has a water influent and produce a process water effluent.

The processes that use only water as ingredient were excluded from the list because no process effluent is produced. The key processes were used in the water pinch.

3.3. Initial water network

Based on the selection of the key processes and potential external user(s), an initial network was made. This initial network has for every process and external user fresh water as influent and every effluent is send to the WWTP. The initial fresh water, $FW_{initial}$, flowrate was calculated with equation (1). The initial wastewater production, $WW_{initial}$, was calculated with equation (2).

$$FW_{initial} = (FW_1 + \cdots + FW_{i-1} + FW_i) + (FW_{ext.1} + \cdots + FW_{ext.k-1} + FW_{ext.k}) \quad (1)$$

$$WW_{initial} = (WW_1 + \cdots + WW_{i-1} + WW_i) + (WW_{ext.1} + \cdots + WW_{ext.k-1} + WW_{ext.k}) \quad (2)$$

3.4. Key constituents in the key process effluents of the brewery

The next step in the screening process was to determine which constituents were present in the effluents produced by the key processes. The criteria for selecting the constituents was based on the influent characteristics, additives of the processes, external additives and losses during production. The last one is called extract losses. From section 2.5.4 the main constituents present in the brewery were determined and used to identify the most relevant constituent, the key constituents. The criteria for the key constituents were;

- A key constituent is the main constituent present in the process effluent of one or more departments
- A key constituent is an important parameter for the agricultural external user
- Key constituent data is available in the brewery
- A key constituent meets all of the criteria stated above.

The constituents that met these criteria were used to complete the water pinch.

3.5. Quantitative data of the key water streams and key constituents in the brewery

Step 6 was to determine quantitative data of the key processes and corresponding constituents. For the water pinch it is necessary to define what the maximum allowable influent and effluent concentrations for the key constituents were. This is important because usually networks without recirculation use fresh water for every process. In this case, all the influent concentrations are similar to the characteristics of the fresh water used. This means that there will be no reuse or recirculation possibilities. So for every key constituent the initial influent and effluent concentration was determined as well as the maximum allowable influent and effluent concentration when possible.

3.5.1. Water flowrate

For the two case breweries a water pinch was applied with actual process water flowrates as well as UBM process water flowrates. For every key process selected, the actual water flowrate was determined based on measured data from the case breweries. The UBM water flowrates were obtained from a database in Heineken. For the processes without UBM value, the actual process water flowrate was used.

3.5.2. COD

The initial influent COD concentration was based on the COD concentration in the water used in the specific processes. From section 2.5 it becomes clear tha the water used in the Heineken brewery is free from COD. No organics are present so the initial influent concentration COD was zero for every process.

The maximum allowable influent concentration COD per process was estimated by employees of the Heineken brewery (Bruijn, 2019). At that moment, no information of best practice concentrations was known to substantiate the estimated values.

The initial effluent concentration COD was calculated with the extract losses per process, measured in the Heineken brewery, and the fact that one litre beer contains 128 g COD. For the brew house and cellars it was assumed that only extract losses are responsible for the COD content in the process effluents. For the packaging area, extra organic material is present due to external filth from returnable crates and bottles. This filth increases the effluent concentration COD. Because this extra amount is unknown and unmeasured in both case breweries, an educated guess was made by employees of the Heineken brewery (Bruijn, 2019). This estimated value was added up to the estimated maximum allowable influent concentration to get the final effluent concentration COD.

3.5.3. Na^+

The initial influent concentration Na^+ per process was based on the Na^+ concentration in the influent water. For processes without additional caustic, the characteristics of Table 5 in section 2.5 were valid. In these processes, the initial effluent concentration Na^+ will be the same as the initial influent concentration. Table 5Section 2.5 shows that the influent waters in the brewery contains zero Na^+ concentration. Therefore, for the processes without caustic the initial influent and effluent concentration Na^+ was 0 mg/L.

The initial influent and effluent concentrations Na^+ for processes with additional caustic are also identical. The caustic used for in the influent stream enters the process and leaves the process without picking up additional Na^+ or leaving Na^+. The initial concentration was calculated with following known parameters;

- Caustic strength of NaOH solution used in Heineken brewery, 2-3% NaOH
- Density of 2% NaOH solution: 1.019 kg/L
- Molar weight NaOH: 40 g/mole
- Molar weight Na^+: 23 g/mole

First, the concentration NaOH in one litre of 2% NaOH solution was calculated with equation 1. The next step was to convert this amount to mol NaOH/L (see equation 2) from where the Na^+ concentration could be calculated with equation 3.

$$\frac{g\ NaOH}{L} = \frac{2}{\left(\frac{100}{density\ NaOH\ 50\% * 1000}\right)} \quad (1)$$

$$\frac{mol\ NaOH}{L} = \frac{\frac{g\ NaOH}{L}}{Molaire\ weight\ NaOH} \quad (2)$$

$$\frac{mg\ Na^+}{L} = \frac{mol\ NaOH}{L} * molaire\ weight\ Na^+ * 1000 \quad (3)$$

For Na^+, the maximum allowable concentrations for influent and effluent are equal to the initial influent and effluent concentrations.

3.5.4. Total N

Similar as the concentration COD, the initial influent concentration Total N was based on the influent water used and the initial effluent concentration was based on the extract losses per process. Section 2.5 shows that the total nitrogen concentration in the brewery influent water is 4 mg/L. The initial influent concentration was therefore 4 mg/L for every process.

The effluent concentration Total N was calculated with the extract losses per process, measured in the case breweries, and the fact that one litre beer contains 0.48 g N. Assumed was that only extract losses were responsible for the Total N content in the process effluents.

For Total N no maximum influent or effluent allowable concentrations could be estimated. Therefore, the initial influent and effluent concentrations of Total N were used in the water pinch.

3.6. Water pinch

When the previous steps in section 3.1 to 3.5 have been applied, enough data is available to construct the composite curves of the water pinch. The composite curve represents how the total system would behave if they were a single water-using process. The composite curve is the transferred mass against the concentration of the constituent (El-Halwagi & Manousiousthakis, 1989). This graphical approach was constructed by calculating for every constituent concentration the transferred mass. Combined with a fresh water supply line, the composite curve identifies the pinch point. The pinch point is de constituent concentration where the fresh water flowrate is at a maximum level. The water supply line and composite curve touch each other at this point. This maximum fresh water volume is the minimum fresh water flowrate required to satisfy the optimal network (Wang & Smith, 1994). In this thesis the minimum water flowrate is targeted with a fixed flowrate approach. Per constituent, a composite curve was constructed by following the steps described in this section.

The equations (4), (5), (6), (7) and (8) are based on research of El-Halwagi and Manousiouthakis (1989) and Castro et al. (1999). The latter one used the theory of El-Halwagi and Manousiouthakis to determine the equations to construct specifically a composite curve in a water pinch.

In short the steps that were taken to construct the composite curve of one constituent are:

1. Calculate the mass load per key process and potential external user
2. Define the amount of constituent concentration intervals
3. Calculate the total flowrate, mass load and cumulative mass load per interval
4. Construct the composite curve by plotting the cumulative mass load against the constituent concentration
5. Calculate the fresh water flowrate per interval
6. Determine the minimum fresh water flowrate for the network by identifying the maximum value from the fresh water flowrates calculated in step 5
7. Draw the fresh water supply line

The first step is to list the key processes and external user(s) with their corresponding water flowrates, f_i, and maximum allowable influent and effluent constituent concentration, $C_i^{lim,in}, C_i^{lim,out}$. With this information known, the mass load, Δm_i, for process or external user i, was calculated with formula (4).

$$\Delta m_i = f_i(C_i^{lim,out} - C_i^{lim,in}) \quad (4)$$

Next, the constituent concentration intervals were determined. The number of intervals, N_{int}, is dependent on the amount of unique values present in the list of limiting influent and effluent constituent concentrations. Equation (5) represents the requirement for the number of intervals based on the number of processes, N_o. The equality of the equation is only applicable when there are no two $C_i^{lim,in}$ and $C_i^{lim,out}$ coincide. The more concentration limitations are similar the less intervals are present.

$$N_{int} \leq 2N_o - 1 \quad (5)$$

The unique constituent concentrations were selected and arranged from lowest constituent concentration to highest constituent concentration. These values relates to the y-axis on the constituent composite curve. An index number was given to each unique value in this list, representing the intervals numbers.

In interval j, the total water flowrate and mass load were calculated. The total water flowrate, $\sum f_j$, in each interval, is the sum of the water flowrates of the processes, i, with their constituent concentration range in that particular interval. The mass load for interval j, was calculated with equation (6).

$$\sum m_j = (\sum_i f_i)_j \, (C_j - C_{j-1}) \tag{6}$$

With $C_{j=0} = min_i(C_{in,max,i})$

Finally, the cumulative mass and thus the mass transferred per interval, was calculated with equation (7). Where $\Delta m_{cumulative,j}$ is the cumulative mass load in interval j.

$$\Delta m_{cumulative,j} = \Delta m_1 + \cdots + \Delta m_{j-1} + \Delta m_j = \sum_{k=1}^{j} \Delta m_k \tag{7}$$

These values correspond to the x-axis of the constituent composite curve.

Next, the pinch concentration per constituent could be determined. This was done by calculating at each interval j, the fresh water flowrate, $f_{ws,j}$, (equation (8)). The interval with the maximum value for the fresh water flowrate represents the minimum fresh water flowrate needed to supply the full network in its most optimized form, see equation (9).

$$f_{ws,j} = \frac{\Delta m_{cumulative,j}}{C_j - C_{j=0}} \tag{8}$$

$$f_{ws,min} = \max\left\{\frac{\Delta m_{cumulative,j}}{C_j - C_{j=0}}\right\} \tag{9}$$

At Interval j, with $f_{ws,min}$, the pinch point is located. The corresponding constituent concentration C_j, and cumulative mass load $\Delta m_{cumulative,j}$, at this interval represent the coordinates of the pinch point. Through the pinch point and the starting point ($\Delta m_{cumulative,j=0}$, $C_{j=0}$), the fresh water supply line was drawn.

The steps above were used to construct for every key constituent a composite curve with water supply line and corresponding pinch point.

3.7. Network design per key constituent

After the composite curves were constructed, per constituent a new network was designed. In the initial network, as drawn in section 3.3, every process influent was fresh water and the effluents were all sent to the WWTP. In the new designs, reuse of process effluents could be possible. The fixed flowrate approach is used in this construction. Usually, dilution of rich streams with lean streams in the fixed flowrate problem is possible, but when a network becomes more complex, it will be more difficult to design a practical network. Therefore, as this is a simplified method to design a network, dilution of streams was excluded.

The first step in designing the constituent network was to determine the sinks and sources. The pinch point in every composite curve represents the concentration where above reuse is possible. In other words, the processes present in the intervals above the pinch point, with an effluent concentration above the pinch concentration, were sinks. The processes present in the intervals below the pinch point were sources, with effluent concentrations below the pinch concentration.

Per constituent a list of sinks was determined with corresponding sources, where $C_{sink,in} \geq C_{source,out}$. As in many cases, multiple sources can satisfy one sink. Usually, first the sink with the strictest water concentration requirement was satisfied, by using a source/sources with the lowest composition (Brouckaert, Gianadda, Schneider, Naylor, & Buckley, 2005). In this way, the fresh water and wastewater flowrates were minimized. However, because the goal of the thesis is to determine to what extend a brewery can be circular on water, the first sink to be satisfied was always the external user(s). The external user was satisfied with every possible source until it was completely satisfied or no sources were left. After that, in sequential order the rest of the sinks were satisfied based on their water requirement concentration by using sources, starting with the source with the lowest constituent composition. In case there was not enough source water to satisfy a sink, fresh water was added to fill the gap. It is possible that there were sources that could not satisfy a sink or the other way around, there were sinks that had no source. This could happen because the external user was satisfied first although it might not have the strictest water concentration requirements. Therefore, some processes that were marked as sink or source could not participate in the redirection network. For every source and sink without reuse possibilities or source water, fresh water was used as influent. All the process effluents that were not redirected to another process or external user, were send to the WWTP.

For the new network, the new required fresh water flowrate, FW_{new}, was calculated by adding the process water flowrates that require fresh water. The new wastewater production is the sum of all the process effluents that were send to the WWTP. The degree of circularity* of the network is calculated by the difference between brewery fresh water flowrate and the brewery effluent flowrate that is sent to the external user. For example;

The new fresh water flowrate of the brewery is 1000 m^3/month and the new wastewater production is 800 m^3/month. Of the 200 m^3/month difference, 150 m^3/month is sent to the external user and 50 m^3/month is redirected internally. Therefore the brewery is 19% circular on water.*

3.8. Reference constituent and integrated network

When for every constituent a network was designed, the reference constituent could be indicated. The reference constituent was the constituent that had a network that required the highest total fresh water flowrate. This constituent is limiting because it has the most limitations compared to the other constituents.

The next step was to check if the network based on the reference constituent could also apply to the other constituent restrictions. This was done by checking if the redirected streams in the reference constituent network were also an option according to the limiting in- and effluent concentrations of the other constituents. Per recirculation option the limiting effluent concentration of the other constituents of the source were compared to the maximum allowable influent concentration of that constituent in the sink. For example;

The effluent of process 1 is in the reference constituent 'A' network redirected to process 6. But for process 6 the maximum allowable influent concentration for constituent 'B' is lower than the effluent concentration of constituent 'B' in process 1. This means that according to constituent 'B' the recirculation between process 1 and 6 is not possible. This option should be deleted in the integrated network.

The network requirements were updated after the check and an integrated network was designed that satisfied all constituent concentration restrictions.

4. Results

In this chapter the results are presented for two case breweries. Despite the fact that a brewery in its origin is quite simple, the way in which the processes are executed are different for every brewery. Generic, average data of water and chemical use in a brewery is hard to find. Therefore, as the water pinch is dependent on specific data, example breweries were chosen to serve as a case study. With the case brewery El Obour, every step in the water pinch analysis is described in detail. This is to show how a water pinch can be applied to a brewery or any other network. To analyse the circularity concept and breweries in combination with the water pinch, more results were necessary to validate the findings from the first case study. Therefore, another brewery, Sharkia, was used. The results of Sharkia were obtained in the same way as the results of El Obour but only the relevant details and results are shown in this thesis.

4.1. Case description

Heineken has 27 breweries that were marked as water stressed breweries, see Figure 10. These breweries were selected for the Every Drop program of Heineken. The strategy of the Every Drop program is to first increase water efficiency in the water stressed breweries followed by decreasing the impact on the local watersheds with the help of circularity. As the water pinch is mainly designed to decrease fresh water consumption and wastewater production in a network, water scarce areas are a logical work field when it comes to efficiency and circularity. Two breweries were selected, both in Egypt, El Obour brewery and Sharkia brewery, see detailed map Figure 10. Both have already a reasonable water efficiency and could therefore move their focus towards circularity. The breweries serve as representative for the 27 breweries located in water stressed areas (see Figure 10).

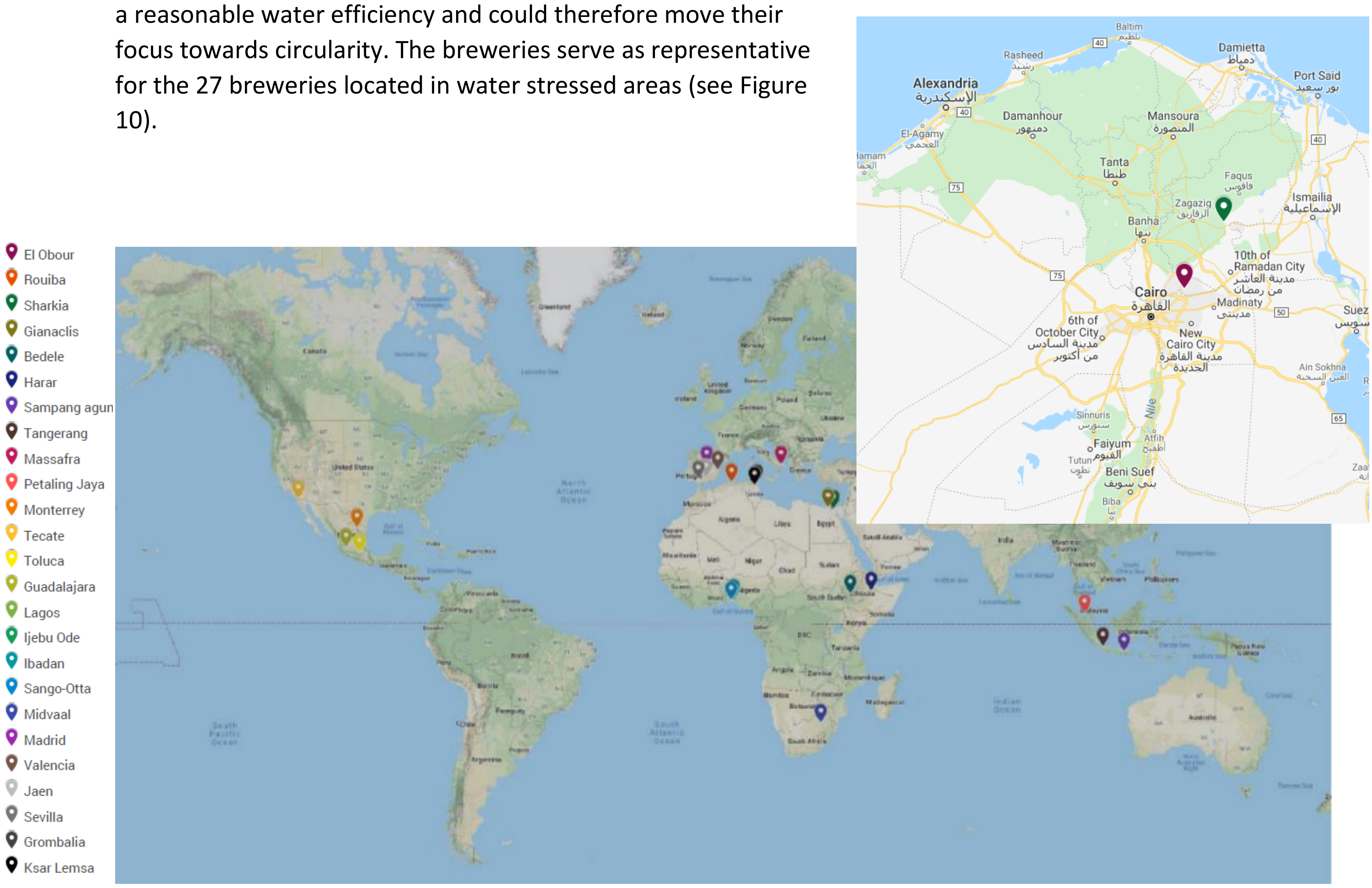

Figure 10: 27 Heineken breweries classified as water stressed breweries. In detail the two breweries in Egypt were shown.

4.1.1. El Obour brewery

The El Obour brewery is part of Al Ahram beverages and is located in the outskirts of Cairo. The El Obour brewery is a brewery that produces mainly beer in cans, 52% of the total volume produced. The other part is produced for the returnable bottles (33%) and kegs (15%). The climate in Egypt is classified as hot desert climate, which means high temperatures, lots of sun, high humidity and no to very little rain all year (Köppen, 1900). The main fresh water source in Egypt is the Nile River. Besides the Nile River, groundwater aquifers also provide fresh water. However, due to uneven water distribution and pollution of fresh water sources, the water availability has decreased over time. Egypt is classified as water scarce.

The El Obour brewery is located in an industrial, dry area. With google maps possible agricultural external users were identified in the neighbourhood of the El Obour brewery. As Figure 11 shows, in a distance of 2.5 km as the crows flies, an orange orchard is located. Because only data from google maps was available and no real time confirmation, the orange orchard is estimated to be 87 ha (orange area in Figure 11). The orange orchard is the only potential, agricultural, external user in the surroundings of the El Obour brewery used in this case study.

4.1.2. Sharkia brewery

The Sharkia brewery is part of the Al Ahram beverages as well but is located more in the north of Egypt. In the Sharkia brewery 55% of the total volume produced is packed in cans. The other half is divided over returnable bottles (24%) and PET bottles (21%). The brewery is located in the Nile delta, a somewhat greener area than the El Obour brewery, see Figure 11 and Figure 12. From google maps several agricultural land is identified in the surroundings of the brewery. A land area of 87 ha was selected to serve as an example farmer. As citrus is the major fruit crop in Egypt, this land area is considered as an orange orchard (Abobatta, 2018). Figure 12 shows that the location of the orange orchard close to Sharkia is at a distance of 2.6 km as the crow flies. In this case, the two situations are similar and can easily be compared.

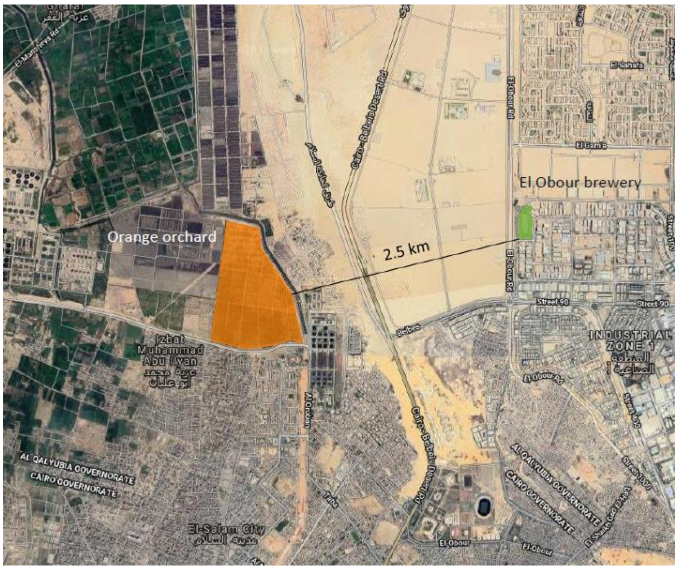

Figure 11: El Obour brewery (green) and orange orchard (orange) location

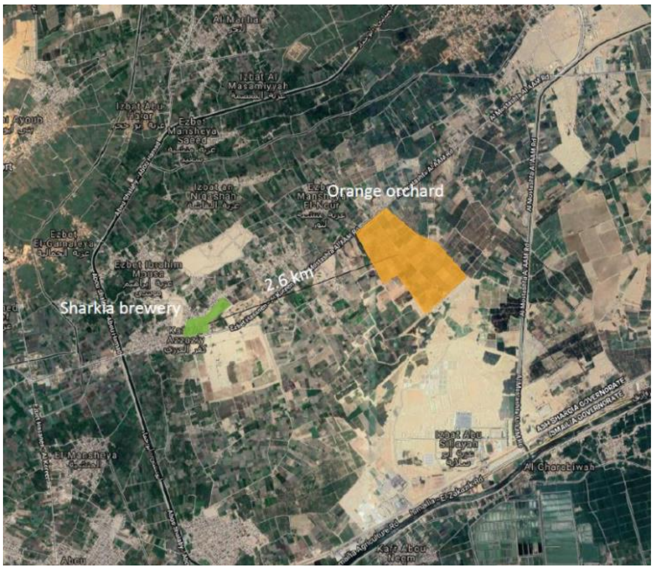

Figure 12: Sharkia brewery (green) and orange orchard (orange) location.

4.2. Key processes and key constituents in the Heineken breweries

Based on the criteria that every key process should have a water influent and a process water effluent, the key processes in the El Obour and Sharkia brewery were selected. Table 6, first column, shows per department the key processes for El Obour. These key processes were also selected based on the fact that the El Obour brewery had data available for these processes. In the last column of Table 6 the key processes for the Sharkia brewery were shown. These were also selected based on the data availability in the brewery.

The difference in processes is that in the Sharkia brewery part of the produced beer volume is packed in PET bottles instead of kegs. Therefore, no keg washer is present in the Sharkia brewery but instead a PET filler + rinser and PET pasteurizer are added to the list. Also in the Sharkia brewery no BMF and PVPP air removal water is used, this is because there is no such installation.

Table 6: Key processes per department for the Heineken case breweries

Department	***Processes El Obour***	***Processes Sharkia***
Brew house	CIP brew house	CIP brew house
	CIP wort copper	CIP wort copper
	CIP wort cooler	CIP wort cooler
Cellars	CIP Cellars	CIP Cellars
	Beer membrane filter (BMF) and PVPP air removal	
Packaging	Crate washer	Crate washer
	Bottle washer	Bottle washer
	Bottle filler	Bottle filler
	Vacuum pump	Vacuum pump
	Bottle pasteurizer	Bottle pasteurizer
	Conveyor lubrication	Conveyor lubrication
	Can filler	Can filler
	Can rinser	Can rinser
	Can pasteurizer	Can pasteurizer
	Keg washer	PET filler + rinser
		PET pasteurizer
Utilities	Cooling tower	Cooling tower
	Boilers	Boilers
	CO_2 washer	

Table 7 shows the chosen key constituents for the key processes in the El Obour and Sharkia brewery and their origin, selected on the criteria from section 3.4. As caustic is widely used in the brewery for cleaning purposes and thus ends up in the wastewater stream, sodium was indicated as one of the key constituents. COD was chosen as a key constituent because during the brewing processes high COD levels can occur and ends up in the wastewater via extract losses. The same extract losses contain also an extra key constituent, namely Total Nitrogen.

There are more constituents that could be chosen based on the criteria of main constituent in a stream or important parameter in agriculture. Unfortunately, limited data was available in the case breweries and only these three constituents, data was available.

Important to mention is that the key constituents do not say anything about pathogen microorganisms or toxicity of the water. However, because the water in a brewery is mainly cleanliness these constituents could be considered representative for the water quality.

Table 7: Key constituents present in the key processes for the Heineken breweries

Key constituents	Origin
Chemical oxygen demand (COD)	Organics from beer brewing process, beer losses, organic material from outside the brewery (sand and other dirt in returned bottles, kegs and crates)
Total Nitrogen	Protein breakdown products in extract losses
Na^+	Caustic (sodium hydroxide) in CIPs and bottle/keg/crate washer

4.3. Limited data gathering

4.3.1. Orange orchard data

Key constituents for orange crops were determined with literature information. As mentioned in section 3.1, salinity is one of the most important constituents that can form a threat to crops. In particular sodium can be very dangerous. For oranges this is the case, orange crops are sensitive to sodium toxicity (Ayers & Westcot, 1985). Therefore, sodium is a key constituent for the orange plants. Other important constituents for plants are nutrients in the form of phosphorus and nitrogen. For the growth of plants and fruits nitrogen is vital. But on the other hand, a surplus of nitrogen can be dangerous. Therefore Total N was also considered as a key constituent for orange plants.

COD is an important key constituent from the brewery effluents but is usually not considered as a main parameter in irrigation water for oranges. This is mainly because COD can be advantageous because organic substances can enrich the soil (Ayers & Westcot, 1985). However, limits for COD are given in many irrigation water quality guidelines because of the transportation and storage involved. Too high COD concentrations can indicate high organic loads causing anaerobic conditions when process effluent is stored. Furthermore, it can cause growth of microorganisms in the transportation system (Ayers & Westcot, 1985). Especially biodegradation is a threat because it can clog the transportation equipment. For these reasons, COD is an important constituent and can be selected for the oranges as well.

Table 8 shows the limited data for orange irrigation water. Due to limitations of time and resources, literature was used to quantify data for the orange orchard. In a research of McMahon et al. (1989) towards citrus irrigation with reclaimed wastewater in Florida, the maximum concentration of constituents was determined. This was in collaboration with the Institute of Food and Agricultural Sciences (IFAS) Citrus Research and Education Center (McMahon, Koo, & Williams Persons, 1989). By taking samples, the maximum average allowable concentration was determined of several constituents in irrigation water. The concentrations for the used constituents are shown in Table 8. Another research in Florida with reclaimed wastewater as irrigation source for oranges concluded that the plants watered with reclaimed wastewater were more vigorous and produced more fruits (Maurer, Davies, & Graetz, 1995). Besides, less fertilizer was needed because of the presence of nutrients P, N and K, which reduces the risks of surface water and/or groundwater contamination (Sanderson, 1986). The wastewater used in this research originated from a municipal WWTP, these characteristic are also shown in Table 8. These values are not limiting values as this is just one example. However, this is an extensive research of several years making it a good example to show to what extend oranges can handle the constituents. For the water pinch the values of the two researches are used to determine the maximum limiting influent value for orange irrigation water (see Table 9).

Table 8: Irrigation water quality guidelines orange plants

Constituent	Unit	Concentration limit	Reference
EC_w	dS/m	1.1	(McMahon, Koo, & Williams Persons, 1989)
		0.8	(Maurer, Davies, & Graetz, 1995)
Na^+	mg/L	70	(McMahon, Koo, & Williams Persons, 1989)
		136	(Maurer, Davies, & Graetz, 1995)
Cl^-	mg/L	100	(McMahon, Koo, & Williams Persons, 1989)
		-	(Maurer, Davies, & Graetz, 1995)
B^+	mg/L	1.0	(McMahon, Koo, & Williams Persons, 1989)
		0.42	(Maurer, Davies, & Graetz, 1995)
pH	-	6.5-8.4	(McMahon, Koo, & Williams Persons, 1989)
		7	(Maurer, Davies, & Graetz, 1995)
COD	mg/L	120	(McMahon, Koo, & Williams Persons, 1989)
		-	(Maurer, Davies, & Graetz, 1995)
Total P	mg/L	10	(McMahon, Koo, & Williams Persons, 1989)
		3.88	(Maurer, Davies, & Graetz, 1995)
Total N	mg/L	30	(McMahon, Koo, & Williams Persons, 1989)
		5.61	(Maurer, Davies, & Graetz, 1995)

Besides the aforementioned constituents, accumulation of heavy metals in the soil of crops can cause issues (Almeelbi, Ismail, Basahi, Qari, & Hassan, 2014). But as brewery wastewater doesn't contain any heavy metals (see section 2.5 for water characteristics) this is not an issue and this was not taken into account.

The effluent concentrations for the key constituents were not found in literature. As shown in Table 9, the effluent limited concentrations were set to a maximum concentration of respectively, 1500 mg COD/L, 100 mg Total N/L and 3000 mg Na^+/L. This was done because there is no real effluent from an orange orchard, the water is infiltrated in the soil. However, to model the orange orchard in the water pinch, an effluent concentration is necessary. To avoid that the effluent from the orange orchard was identified as possible source for other processes, the effluent concentrations were all set above the highest effluent concentration for COD and Total N of the brewery processes and a maximum of 3000 mg/L for Na^+.

The water consumption of oranges trees is highly dependent on tree size, climate, soil and citrus specie. To be able to use the orange orchard in the water pinch, an orchard of mature trees with a canopy diameter of 16ft was used. Based on research of the University of Arizona the average monthly water consumption was estimated to be 9836 m^3/month (Wright, 2000).

Table 9: Limited data of orange orchard. The water flowrate required per month is shown as well as the maximum allowable influent and effluent concentrations for the key constituent COD, Total N and Na^+ based on literature data (Table 8)

Key process	***Process*** [No.]	***Water flow*** [m^3/month]	***$COD_{lim, in}$*** [mg/L]	***$COD_{lim, out}$*** [mg/L]	***Total $N_{lim, in}$*** [mg/L]	***Total $N_{lim, out}$*** [mg/L]	***$Na^+_{lim, in}$*** [mg/L]	***$Na^+_{lim,out}$*** [mg/L]
Orange orchard	20	9836	120	1500	30	100	70	3000

4.3.2. Brewery data

After the key processes and key constituents were selected, the limited data was collected from measured data in the El Obour and Sharkia brewery as well as with the help of long time experience from Heineken employees. UBM data was obtained from the Heineken database. General brewery data of total volume produced, total volume of bottles, cans and kegs is listed in Table 10. This data was used in the calculations for the key constituent concentrations.

Table 10: General brewery data of average total beer volume produced, total bottled volume, total canned volume, total volume in kegs and total PET volume for the El Obour brewery and Sharkia brewery. Data of El Obour based on monthly data from the year 2018 and 2019. Sharkia data based on month September 2019.

	El Obour brewery [hL/month]	Sharkia brewery [hL/month]
Total volume produced	70941	126781
Total volume bottled	18698	13847
Total volume canned	40673	57962
Total volume keg	11569	0
Total volume PET	0	56437

Table 11 shows the limiting data for the three key constituents COD, Total N and Na^+ in mg/L and the actual process water flowrate in m^3/month for the El Obour brewery. The actual water flowrate for the key processes is determined with monthly data from the El Obour brewery of 1.5 years measurements. For the processes with available UBM values, the UBM water flowrate is presented in m^3/month in a separate table with new COD, Total N and Na^+ concentrations in Appendix 1, Table 23. The processes that had no UBM value available kept the actual process water flowrate in the water pinch calculations.

The limited COD influent concentration is the maximum allowable influent concentration based on estimations of Heineken employees (see section 3.5.2). The limited effluent concentration is determined with measured data based on extract losses from the brewery and the estimated influent concentration. Extract losses can be found in Appendix 2, Table 25. An example of the calculation of the COD concentration based on the extract losses can be found in example 1.

Example 1: Calculation limited effluent concentration COD for the bottle filler, process 11

Extract loss bottle filler = 1.33% of total bottled beer volume
Total bottles beer volume El Obour = 18698 hL/month
Estimated COD extra due to external factors = 0 mg/L

$$COD_{lim,out} = COD_{lim,in} + \frac{Total\ bottled\ beer\ volume \times 128 \frac{gCOD}{L\ beer} \times extract\ loss}{FW_{process\ 11}} + COD_{extra}$$

$$COD_{lim,out} = 30 + \frac{18698 \times 128 \times 1.33\%}{259} + 0 = 153\ mg/L$$

For Na^+ and Total N the limited influent concentrations were determined with measured data from the brewery. The limited effluent concentrations Na^+ were equal to the limited influent concentrations. This is because caustic is already present in the influent water stream and no extra sodium is present in the tanks or pipes that were cleaned. This means that only a dilution could be possible, but for the sake of this research and the lack of detailed data, the limited effluent concentration Na^+ is equal to the limited influent concentration of a process.

The limited effluent concentration of Total N was calculated with the extract losses per process (see Appendix 2, Table 25). Given is that one litre beer contains 0.48 g nitrogen and an easy calculation was done to give the limited effluent concentrations of Total N. The calculation for the bottle filler is shown in example 2;

Example 2: calculation limited effluent concentration Total N for the bottle filler, process 10

Extract loss bottle filler = 1.33% of total bottled beer volume
Total bottles beer volume El Obour = 18698 hL/month

$$Total\ N_{lim,out,bottle\ filler} = Total\ N_{lim,in} + \frac{total\ bottled\ beer\ volume \times 0.48 \frac{gN}{L\ beer} \times extract\ loss}{FW_{process\ 11}}$$

$$Total\ N_{lim,out,bottle\ filler} = 4 + \frac{(18698)\times(0.48)\times(1.5\%)}{885} = 4.46\ mg/L$$

Table 11: Limiting data for key processes from El Obour brewery. Per key process, the actual water flowrates are presented in m³/month and COD, Total N and Na⁺ in- and effluent concentration are given in mg/L. Data based on Heineken measurements and information.

[No.]	Key process	$f_{i,actual}$ [m³/month]	$COD_{lim,in}$ [mg/L]	$COD_{lim,out}$ [mg/L]	Total $N_{lim,in}$ [mg/L]	Total $N_{lim,out}$ [mg/L]	$Na^+_{lim,in}$ [mg/L]	$Na^+_{lim,out}$ [mg/L]
1	CO2 washer	596	0	0	4.00	4.00	0	0
2	Boilers	75	0	0	4.00	4.00	0	0
3	Cooling towers	1137	150	150	4.00	4.00	0	0
4	CIP brew house	709	0	8	4.00	4.38	11719	11719
5	CIP wort copper	213	0	1408	4.00	5.28	11719	11719
6	CIP wort cooler	993	0	8	4.00	4.27	11719	11719
7	BMF and PVPP air removal	142	0	27	4.00	10.48	0	0
8	CIP Cellars	1419	0	1427	4.00	4.65	11719	11719
9	Crate washer	93	250	1450	4.00	4.00	4073	4073
10	Bottle washer	885	200	1400	4.00	4.15	6453	6453
11	Bottle filler	259	30	153	4.00	4.46	0	0
12	Vacuum pump	853	200	200	4.00	4.00	0	0
13	Bottle pasteurizer	1146	50	1353	4.00	4.01	0	0
14	Conveyor lubrication	256	100	241	4.00	4.53	0	0
15	Can filler	169	30	339	4.00	5.16	0	0
16	Can rinser	169	30	32	4.00	4.00	0	0
17	Can pasteurizer	184	50	335	4.00	5.06	0	0
18	Keg washer	457	0	1200	4.00	4.18	12508	12508

The limited data for the Sharkia brewery was collected similar to the data gathering of the El Obour brewery. Table 12 shows the data per key process of Sharkia used for the water pinch with actual process water flowrate. Appendix 1, Table 24, shows the data for Sharkia with UBM process water flowrates. The extract losses per processes are shown in Appendix 2, Table 26.

Table 12: Limiting data per process for Sharkia brewery. Per key process, the actual water flowrates are presented in m^3/month and COD, Total N and Na^+ in- and effluent concentration are given in mg/L. Data based on Heineken measurements and information.

[No.]	Key process	$f_{i,actual}$ [m³/month]	$COD_{lim, in}$ [mg/L]	$COD_{lim, out}$ [mg/L]	Total $N_{lim, in}$ [mg/L]	Total $N_{lim, out}$ [mg/L]	$Na^+_{lim, in}$ [mg/L]	$Na^+_{lim,out}$ [mg/L]
1	Boilers	1080	0	0	4.00	4.00	0	0
2	Cooling towers	2300	150	150	4.00	4.00	0	0
3	CIP brew house	73	0	0	4.00	5.25	11719	11719
4	CIP wort copper	46	0	1403	4.00	5.98	11719	11719
5	CIP wort cooler	21	0	7	4.00	8.35	11719	11719
6	CIP Cellars	5400	0	1400	4.00	4.05	11719	11719
7	Crate washer	10	250	1450	4.00	4.00	38080	38080
8	Bottle washer	2100	200	1400	4.00	4.00	2720	2720
9	Bottle filler	25	0	1	4.00	4.44	0	0
10	Vacuum pump	852	200	200	4.00	4.00	0	0
11	Bottle pasteurizer	957	50	1350	4.00	4.00	0	0
12	Conveyor belt smoother	430	100	100	4.00	4.00	0	0
13	Can filler	173	30	32	4.00	5.12	0	0
14	Can rinser	560	30	30	4.00	4.00	0	0
15	Can pasteurizer	212	50	50	4.00	4.00	0	0
16	PET filler + rinser	1260	0	1	4.00	4.15	0	0
17	PET pasteurizer	196	0	0	4.00	4.01	0	0

With the data from the El Obour brewery Table 11, the water pinch is described in detail in the next sections. The other brewery data is used to apply the water pinch on in the same way as the El Obour brewery with process water flowrates. However, only the relevant results and the design for the integrated networks are shown.

4.4. Initial water networks – breweries and external user

With the data from Table 9 and Table 11, an initial water network for the El Obour brewery and external user, orange orchard, was designed. Every process had in this case the required fresh water influent and every process effluent was sent to the WWTP. The total fresh water flowrate that is required in this initial network, is the sum of the water flowrates in the brewery including the orange orchard water flowrate. The total wastewater production in the network is equal to the total fresh water flowrate. In Figure 21 in Appendix 3, the initial water network for the El Obour brewery with actual water flowrates is shown. The process numbers 1 through 18 correspond to the processes in Table 11, with process 20 representing the orange orchard from Table 9. The initial water network with UBM values is similar and can be found in Appendix 3, Figure 22. The required total fresh water and total wastewater production flowrates for the initial networks for El Obour, are shown in Table 13.

Table 13: Total fresh water flowrate for the initial networks based on actual process water flowrates and UBM process water flowrates. The initial wastewater production is equal to the initial fresh water flowrate. Complete network contains El Obour brewery and orange orchard (process 1 through 18 and 20). Brewery only is process 1 through 18.

Network type	$FW_{initial,complete}$ **[m³/month]**	$FW_{initial,brewery\ only}$ **[m³/month]**
Based on actual water flowrates	19592	9755
Based on UBM water flowrates	18302	8466

For Sharkia the data from Table 9 and Table 12 was used to construct the initial networks for the actual process water flowrates as well as the UBM process water flowrates. Every process was supplied with fresh water and every process effluent was sent to the WWTP. The initial fresh water flowrates for the two networks are shown in Table 14. The initial wastewater production is equal to the fresh water flowrate as there is no recirculation or redirection of streams. The initial network designs can be found in Appendix 3, Figure 23 and Figure 24.

Table 14: Initial fresh water production for the Sharkia brewery with actual and UBM process water flowrates. The initial wastewater production is equal to the fresh water flowrate. Complete network contains Sharkia brewery and orange orchard (process 1 through 17 and 20). Brewery only is process 1 through 17.

Network type	$FW_{initial,complete}$ **[m³/month]**	$FW_{initial,brewery\ only}$ **[m³/month]**
Based on actual water flowrates	25531	15695
Based on UBM water flowrates	24797	14961

4.5. El Obour Water pinch - Actual situation

Per key constituent a composite curve and network design with the orange orchard was made. In the sections 4.5.1, 4.5.2 and 4.5.3 the results are shown. Per constituent, the steps 1 through 7 from section 3.6 were followed. For COD as limiting constituent, the construction of the composite curve and network was described in detail. For Na^+ and Total N only the composite curve and designed network were shown as they were constructed in the same way.

4.5.1. COD as limiting constituent El Obour

Construction of the composite curve

The composite curve is a representation of all the processes in a network as one single process. Therefore, the composite curve is a combination of all the mass transfers in the individual processes. An example is made with four processes from the El Obour brewery to show how a composite curve was constructed in this research. See example 3 below.

Example 3: Construction the composite curve with water supply line for COD as limiting constituent

This is an example to construct the composite curve for a network with four processes, the BMF and PVPP air removal, the can filler, the can pasteurizer and the crate washer from El Obour brewery.

The first step in construction of the composite curve is to calculate the mass load per process. This was done with formula (4), see example calculation below for the can pasteurizer, process number $i = 17$*. In Table 15 the mass load,* Δm_{i}*, for the four processes is shown.*

Example of calculation mass load process 17, can pasteurizer

$$\Delta m_{17} = f_{17}\left(COD_{17}^{lim,out} - COD_{17}^{lim,in}\right)$$

$$\Delta m_{17} = 184\ m^3/month\ \times (181\ mg\ COD/L - 50\ mg\ COD/L)\ = 24\ kg\ COD/month$$

Table 15: Process characteristics for four brewery processes used in example 3, based on data in Table 11.

Process No.		$f_{i,actual}$ [m³/month]	$COD_i^{lim,in}$ [mg/L]	$COD_i^{lim,out}$ [mg/L]	Δm_i [kg/month]
7	***BMF and PVPP air removal***	142	0	27	4
15	***Can filler***	169	30	339	52
17	***Can pasteurizer***	184	50	181	24
9	***Crate washer***	93	250	1450	112

With the mass loads per process, a single process composite curve was constructed. In the graphs of Figure 13, a composite curve of the BMF and PVPP air removal, the can filler, the can pasteurizer and the crate washer was made based onthe mass load and the in- and effluent COD concentrations. The next step is to combine these composite curves to one curve representing the complete network of four processes. Figure 14 shows the combination graph of the individual processes. The process with the lowest influent COD is the starting process and the process with the highest effluent COD is the last process. Every next process starts at the mass load of the previous process as this is already in the system. In this example BMF and PVPP air removal is the first process starting at (0,0) and ends at a mass load of 4 kg/month at COD_{out} *of 27 mg/L. The next process, the can filler starts at 4 kg/month and* COD_{start} *= 30 mg/L. With the Δm = 52 kg/month, the can filler ends at 52 + 4 = 56 kg/month and* COD_{out} *= 339 mg/L.*

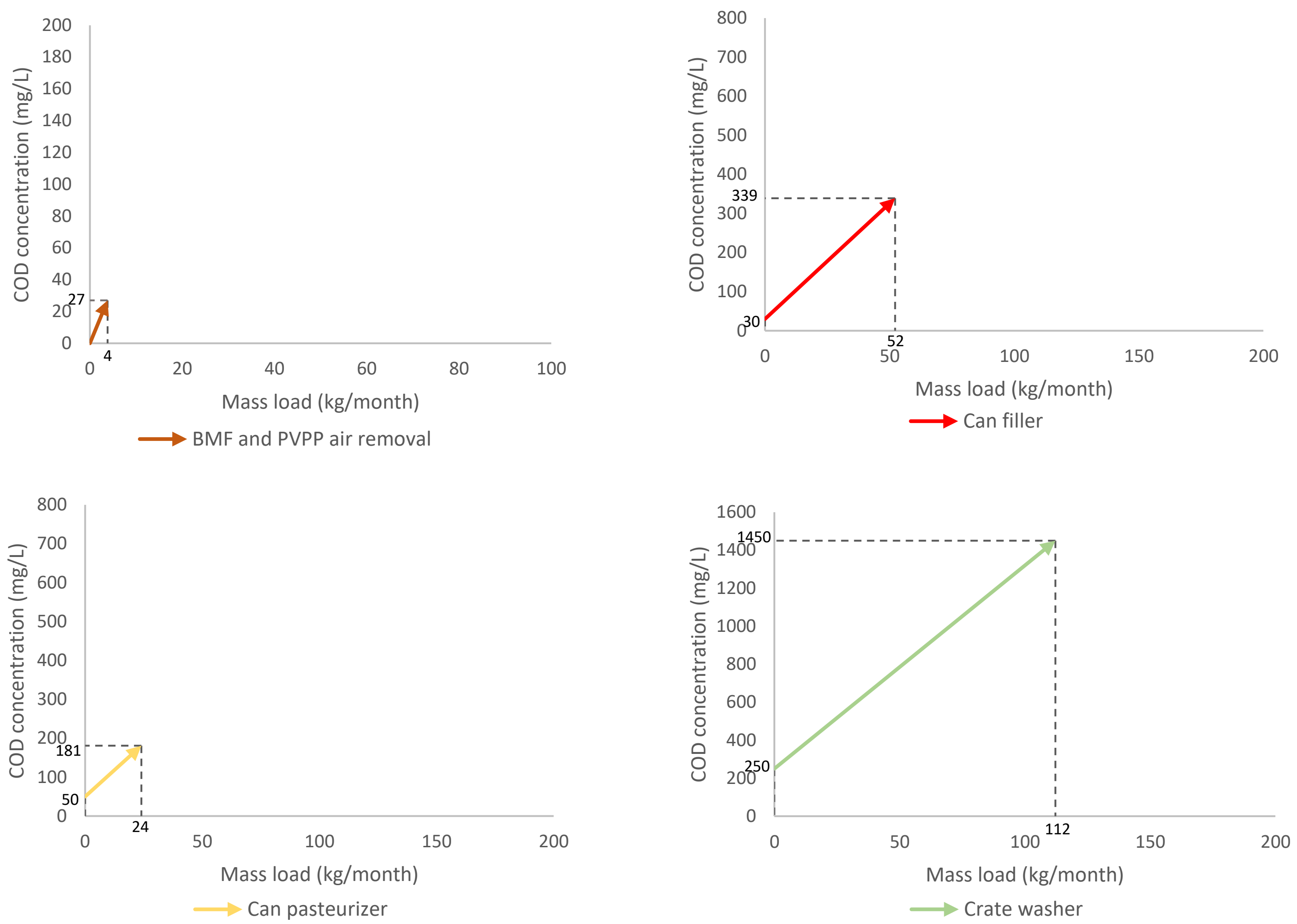

Figure 13: Composite curve for can filler (orange), bottle pasteurizer (red), conveyor belt smoother (yellow) and crate washer (green). The COD concentration per processes is shown with corresponding mass transfer rate. Graphs based on data from Table 15.

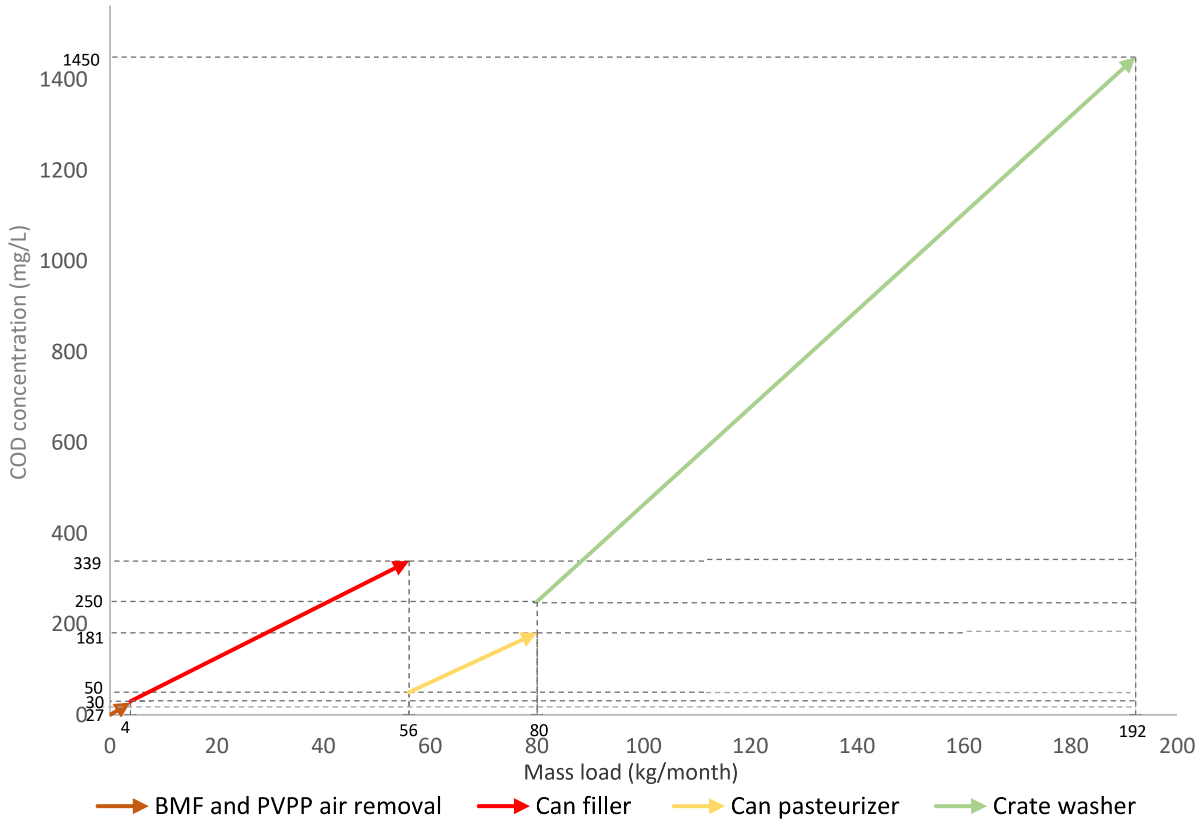

Figure 14: Combined graph with four processes from Table 15 to construct the final composite curve for COD as limiting constituent.

Every in- and effluent concentration COD represent an interval, as shown by the dashed lines in Figure 14. Within each interval the mass transfer rate is constant and determined by the water flowrates of the processes present in that interval (Wang & Smith, 1994). *For example in interval 50 mg/L to 181 mg/L COD, the interval is defined by the in- and effluent concentration of the can pasteurizer. In this interval, the flowrate of the can pasteurizer is present. However, as the can filler has a COD range of 30 mg/L to 339 mg/L, this process is also present in the interval of 50 – 181 mg/L. Accordingly, the mass transfer rate in this interval can be calculated with equation (7) and reads:*

$$mass\ load = \sum m_{50-181\frac{mg}{L}} = \sum f_{50-181\frac{mg}{L}} \times \left(COD_{181\frac{mg}{L}} - COD_{50\frac{mg}{L}}\right) * 10^{-3} = 46\ kg/month$$

With $\sum f_{50-181\frac{mg}{L}} = f_{Can\ pasteurizer} + f_{can\ filler} = 184\frac{m^3}{month} + 196\frac{m^3}{month} = 353\ m^3/month$

As there was already 7 kg/month COD present from the previous interval, the mass load in interval 50 - 181 mg/L starts at 7 kg/month and end at 46 + 7 = 53 kg/month.

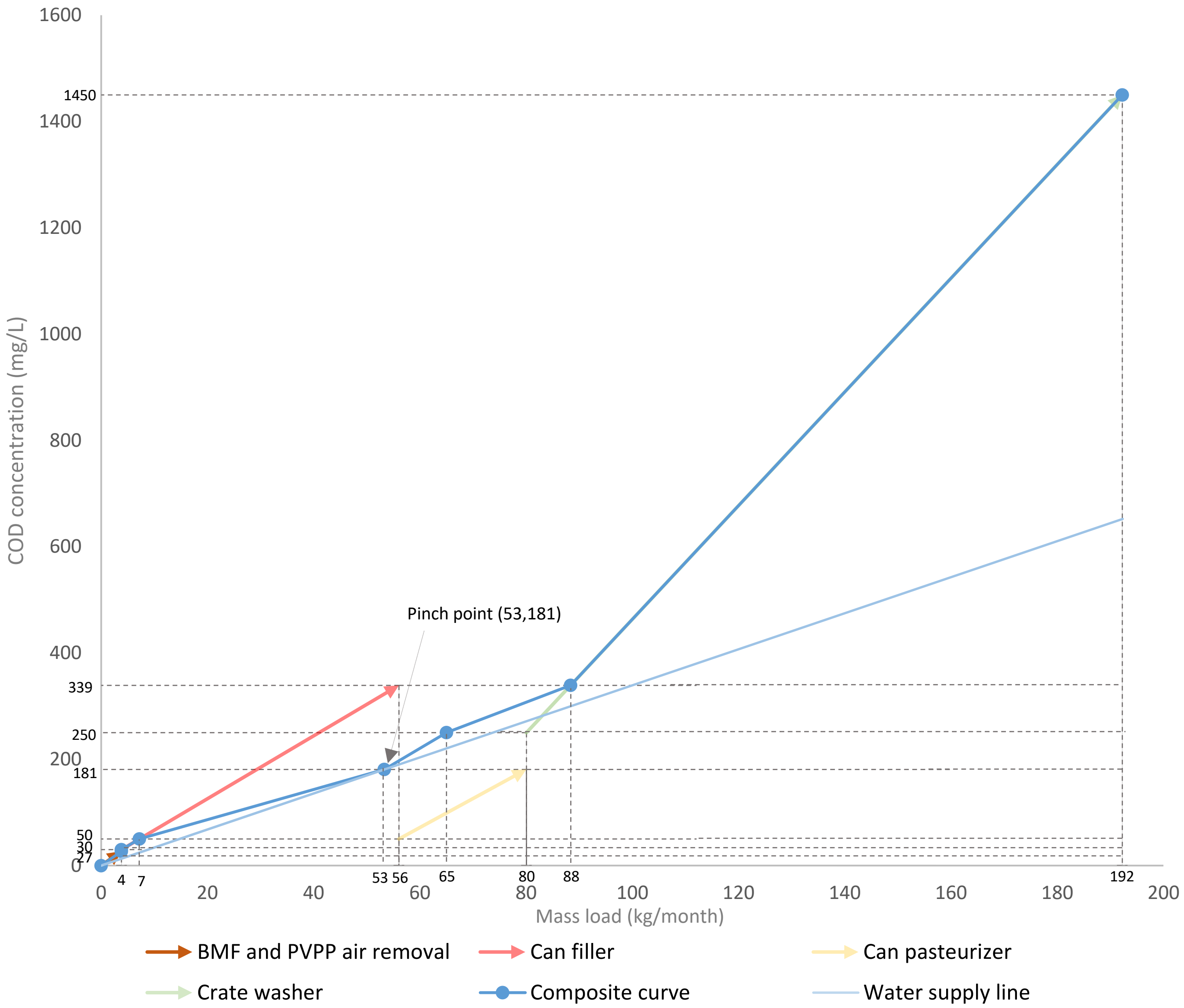

Figure 15: Composite curve with COD as limiting constituent for the network from example 3. The arrows represent the individual brewery process mass transfer rates. The blue composite line combines the four processes as a single water-using process. The pinch point is where the water supply line (light blue) touches the composite curve.

For every interval this mass load was calculated and this resulted in a composite curve as shown in Figure 15. The figure shows that the mass rate is constant in every interval but changes slightly because of the present or absence of processes. This composite curve represents the network with the BMF and PVPP air removal, the can filler, the can pasteurizer and the crate washer as a single water-using process.

With the composite curve constructed and mass load known for each interval the minimum fresh water flowrate required to satisfy this network could be calculated. This was done by matching the water supply line with the composite curve. The water supply line touches at, at least one point with the composite curve. First, in each interval the required fresh water flowrate is calculated with equation (9). In this case, fresh water had a COD concentration of 0 mg/L and therefore $C_{j=0} = 0$ mg/L. The minimum required fresh water flowrate to satisfy the network is then the maximum water flowrate calculated. For the network from Figure 15 the maximum fresh water flowrate is located in interval 50 mg/L – 181 mg/L and reads:

$$f_{ws,min} = \frac{\Delta m_{cumulative,50-181\ mg/L}}{C_{181\ mg/L} - C_{j=0}} = \frac{53\ kg\ COD/month}{181\ mg/L - 0\ mg/L} \times 1000 = 295\ m^3/month$$

The coordinates of the point where the water flowrate is at its maximum value represent the pinch point coordinates. Figure 15 shows the pinch point for the example network at mass load of 53 kg/month and a COD of 181 mg/L. This means that every process with a COD effluent concentration > 181 mg/L becomes a sink and every process with a COD effluent ≤ 181 mg/L is indicated as a source. In this small network the BMF and PVPP air removal and can pasteurizer are sources and the can filler and crate washer are sinks. The composite curve with water supply line can be used to design the optimized network.

For the complete El Obour brewery network the steps from example 3 were applied to construct the composite curve with water supply line. Based on the information stored in Table 11, column $COD_i^{lim,in}$ and $COD_i^{lim,out}$ and the orange orchard characteristics from Table 9, 21 unique COD concentration values were determined. This means that there were 21 intervals. The list of intervals and corresponding COD ranges is shown in Appendix 4a, Table 27. The number of intervals comply with equation (5) but because there are concentrations that coincide, the equality of equation (5) is not valid.

$$N_{int} \leq 2N_o - 1 \qquad (5)$$

Now per interval the flowrate, mass load and cumulative mass load were calculated with equation (6), (7) and (8). Example 4 shows the calculations for interval $j = 4$ with COD concentration range of 30 – 32 mg/L. This interval includes the processes keg washer (no. 18), CIP wort copper (no. 5), CIP cellars (no. 8), can rinser (no. 16), can filler (no.15) and bottle filler (no.11). For these processes the required water flowrate is summed to get the total water flowrate in this interval $\sum f_{j=4}$.

Example 4 of calculations in interval 4 El Obour network; flowrate, mass load and cumulative mass load

$$Water\ flowrate = \sum f_{j=4} = f_{i=5} + f_{i=8} + f_{i=11} + f_{i=15} + f_{i=16} + f_{i=18} = 2686\ m^3/month$$

$$mass\ load = \sum m_4 = \sum f_{j=4} \times (COD_4 - COD_3) = 2686\ m^3/month \times (32 - 30) = 5\ kg\ COD/month$$

$$Cumulative\ mass\ load = \Delta m_{cumulative,4} = \Delta m_1 + \Delta m_4 + \Delta m_3 + \Delta m_4 = 31 + 42 + 6 + 5 = 85\ \text{kg COD/month}$$

The complete list of intervals with corresponding flowrate, mass load and cumulative mass load is shown in Appendix 4a, Table 27.

With the intervals and cumulative mass load determined the composite curve could be plotted, with on the x-axis the cumulative mass loads per interval (Appendix 4a, Table 27, column 5) and on the y-axis the COD concentration (Appendix 4a, Table 27, column 2). Figure 16 shows the composite curve for COD as limiting constituent.

For the water supply line per interval the water flowrate was calculated with equation (8) and the full list is shown in Appendix 4a, Table 27, column 6. In the case of COD as limiting constituent, the maximum fresh water flowrate was located in interval 16 at a COD of 1363 mg/L and cumulative mass load of 17770 kg/month. This represents the theoretical minimum fresh water flowrate required in the network. The fresh water flowrate was calculated with equation (9) and for interval 16 this reads:

$$f_{ws,16} = \frac{\Delta m_{cumulative,16}}{C_{j=16} - C_{j=0}} = \frac{17770\ kg\ COD/month}{1363\ mg/L - 0\ mg/L} = 13130\ m^3/month$$

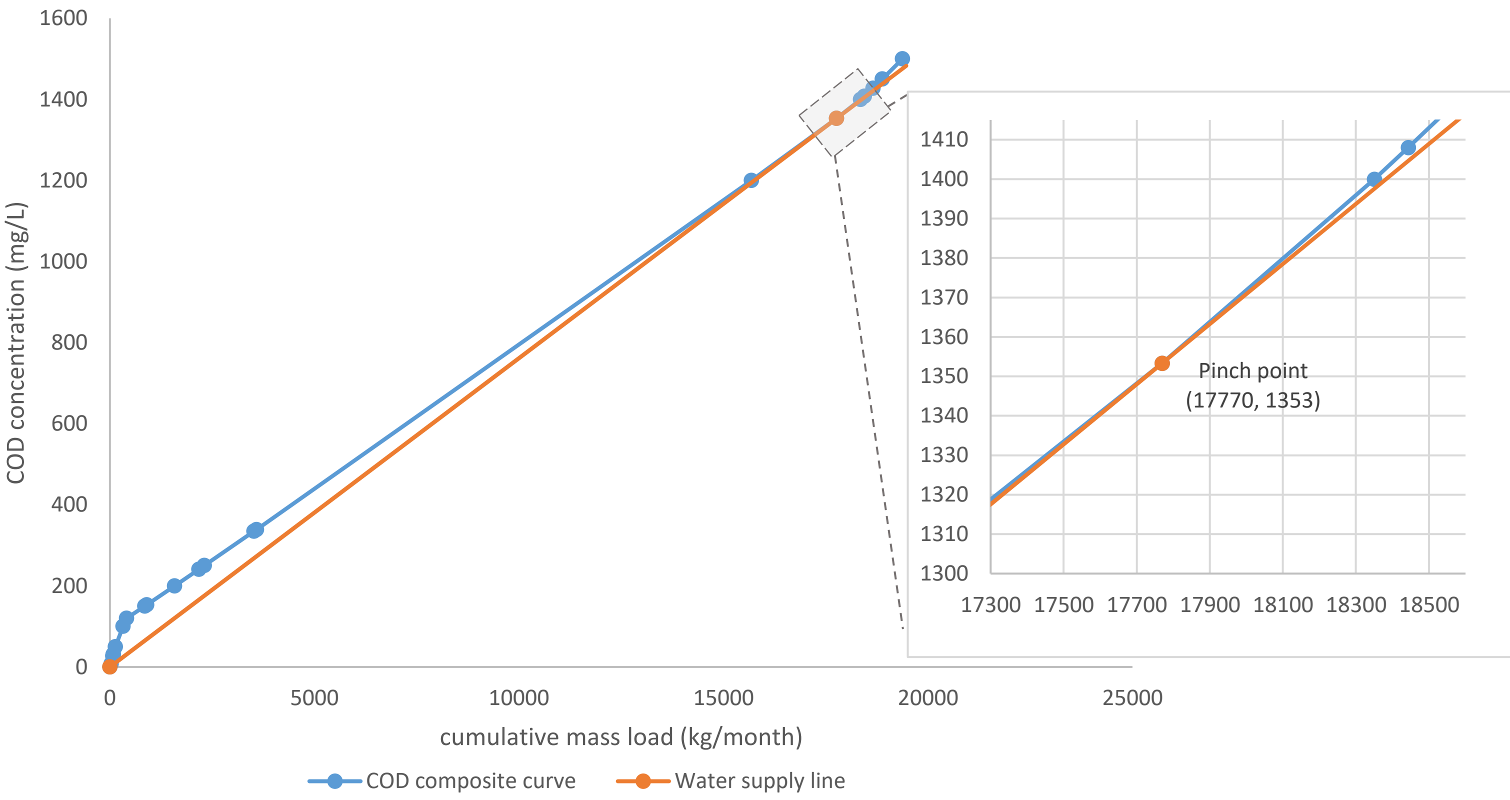

Figure 16 : Composite curve for COD as limiting constituent based on the data from Table 27 in Appendix 3a. The blue line shows the composite curve and the orange line is the fresh water supply line. The pinch point is the point where the water supply line touches the composite curve (see detail).

The pinch point indicates the concentration COD where above reuse of water is possible. From the composite curve in Figure 16 it becomes clear that the pinch concentration is 1363 mg COD/L. This means that every process with a COD effluent concentration higher than 1363 mg/L can reuse water from processes with a COD effluent concentration below 1363 mg/L. A sink is therefore defined as a process j, with $COD_j^{lim,out} > COD_{pinch\ point}$ with $COD_{pinch\ point,El\ Obour\ actual} = 1363\ mg/L$.

In Table 16 and Table 17 the sinks and sources are shown with the maximum allowable influent concentration for the sinks and the maximum effluent concentration for the sources. This is to indicate quickly which source could be used for which sink.

Table 16: Sinks in the El Obour brewery network based on COD composite curve from Figure 16

Process No.	Sink	$COD_i^{lim,in}$ [mg/L]	f_i [m^3/month]
5	CIP wort copper	0	213
8	CIP cellars (BBT and mixing tanks)	0	1419
20	Orange plant	120	9836
10	Bottle washer	200	885
9	Crate washer	250	93

Table 17: Sources in the El Obour brewery network based on the COD composite curve from Figure 16

Process No.	Source	$COD_i^{lim,out}$ [mg/L]	f_i [m^3/month]
3	Cooling towers	150	1137
16	Can rinser	32	169
7	BMF and PVPP air removal	27	142
4	CIP brew house	8	709
6	CIP wort cooler	8	993
1	CO_2 washer	0	596
2	Boilers	0	75

Table 18: Processes that were not identified as source or sink in the El Obour network based on the COD composite curve from Figure 16

Process No.		$COD_i^{lim,out}$ [mg/L]	f_i [m^3/month]
17	Can pasteurizer	181	184
12	Vacuum pump	200	853
11	Bottle filler	497	259
14	Conveyor lubrication	634	256
13	Bottle pasteurizer	1363	1146

Network COD

Based on the principle of Brouckaert et al. (Brouckaert, Gianadda, Schneider, Naylor, & Buckley, 2005), as described in the former chapter, the new network with COD as limiting constituent was designed. First, the external user was satisfied, in this case the orange orchard. The maximum allowable influent COD is 120 mg/L, which means that every source with an effluent concentration lower or equal to 120 mg/L can satisfy the orange orchard. From Table 17 it becomes clear that process 1, 2, 4, 6, 7 and 16 meet this requirement. The sum of the process effluents from these processes is 2684 m^3/month, which is lower than the required 9836 m^3/month. However, no other source was available from the brewery with a COD concentration lower than 120 mg/L, thus the gap was filled with fresh water.

Next, the other sinks were satisfied in sequential order of COD concentration from low to high. Process 5 and 8 have a maximum allowable influent COD of 0 mg/L. These sinks could not be satisfied as the external user took all the sources with a COD effluent concentration lower than 120 mg/L. Therefore, process 5 and 8 had to be satisfied with fresh water. The other sinks, process 9 and 10, have a maximum allowable influent concentration of respectively, 250 mg/L and 200 mg/L. The results presented in Table 17 and Table 18 show multiple opportunities to satisfy these two sinks. First, the sink with the strictest maximum allowable influent COD concentration is satisfied with the source with the lowest effluent composition. In this case, process 10 is satisfied first with process 3. However, as process 3 had an actual process effluent flowrate of 1137 m^3/month and process 10 required only 885 m^3/month, part of process 3 could be sent to the next sink. For the next sink, process 9, 252 m^3/month from process 3 was available. As process 9 only required 93 m^3/month, 159 m^3/month from process 3 was sent to the WWTP as there were no other sinks to satisfy.

In Figure 17, the network for COD as limiting constituent in the El Obour brewery is shown. The blue lines indicates fresh water influent, the orange lines indicate effluent streams redirected to other processes or external user and the black lines are the wastewater streams with no destination within the network. The black lines are the streams that will need to go to the WWTP before reuse is possible.

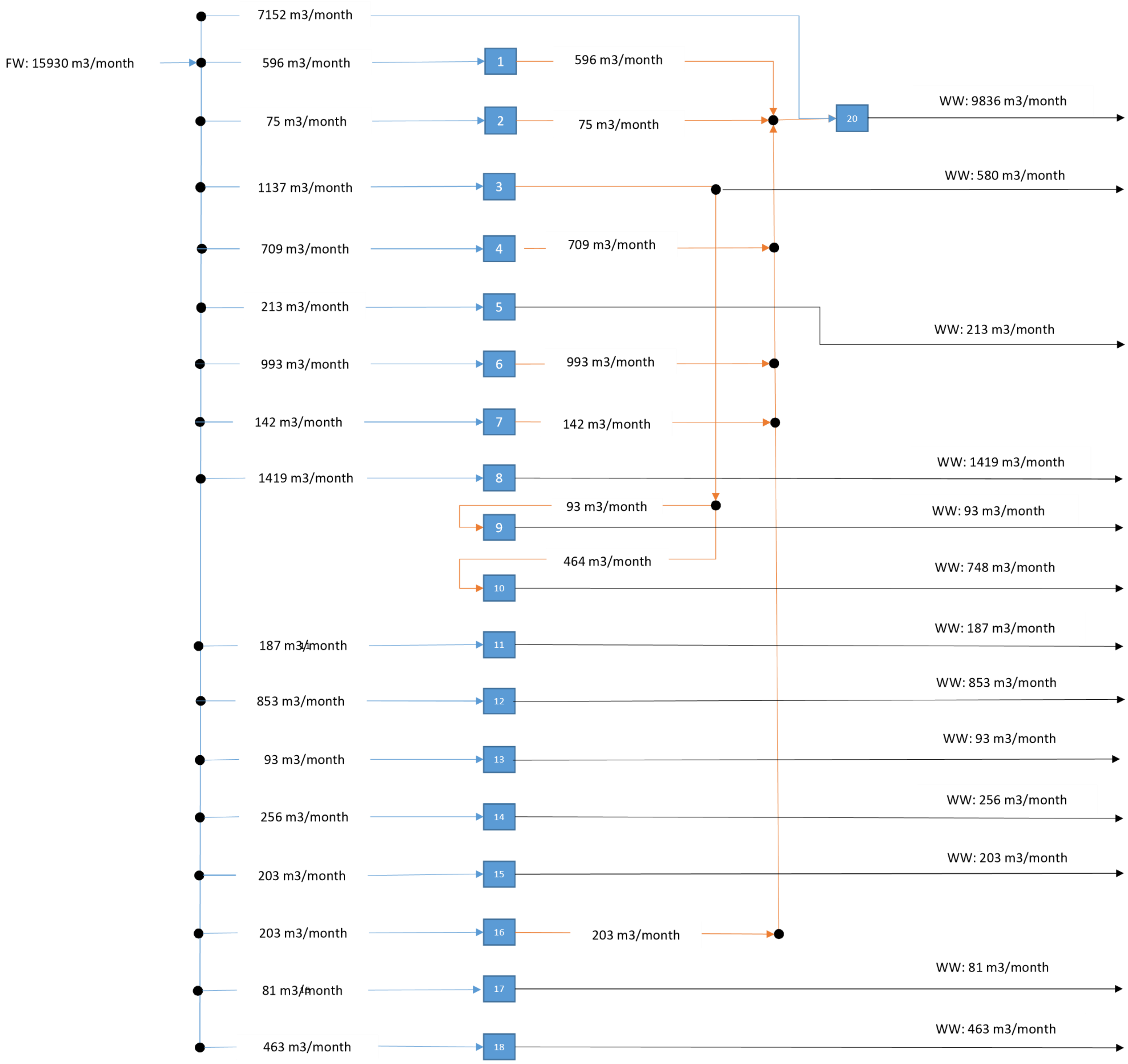

Figure 17: Network design El Obour brewery and orange orchard with COD as limiting constituent. Process 1 till 18 refer to the process numbers in Table 11. Process 20 is the external user, the orange orchard. Blue lines indicate fresh water inflow; orange lines indicate recirculation streams and black lines refer to wastewater sent to the WWTP.

As Figure 17 shows, the fresh water flowrate, FW_{new}, required in this network is 15930 m^3/month. This fresh water flowrate is bigger than the calculated value of $f_{ws,min} = 13130\ m^3/month$ from the composite curve. The explanation for this difference is that mixing of streams was not allowed in the network. The idea of the water pinch is that a multi-user network is modelled as a single water-using process. By dividing the mass transfer between several sources of water, a new network could be designed. Mixing of streams to dilute rich streams and use them as sources is possible to ensure that the minimum water flowrate is obtained (see example in section 2.3.2). However, for practical reasons and to not complexify the network, mixing of streams is not allowed in this network. This caused the somewhat higher fresh water flowrate for the designed network. The network presented in Figure 17 will increase the efficiency of a brewery by reducing the fresh water intake. In this network with COD as limiting constituent the fresh water intake for the brewery is 8777 m^3/month. Compared to the initial brewery network from Appendix 3, Figure 21, the fresh water intake was reduced with 10%. This reduction is because process 9 and 10 could use effluent water from process 3 and do not need fresh water as influent. More importantly, the wastewater production in the brewery has reduced with 38% to 6093 m^3/month. Due to the addition of an external user and reuse of water streams inside the brewery, less wastewater had to be sent to a WWTP. As Figure 17 shows, the process effluents of process 1, 2, 4, 6, 7 and 16 could be sent to the orange orchard, process 20. Therefore, the network designed with COD as limiting constituent is 31% circular* on water.

4.5.2. Na^+ as limiting constituent El Obour

For Na^+ the situation is a bit different from COD. In a water pinch the difference in constituent concentration of the in- and effluent determines the water flowrate necessary. If there is no mass transfer between in and out there is no water flowrate that can satisfy the process. In other words there is nothing to pick up by the water that is supplied. Table 19 shows the processes of the El Obour brewery and the characteristics for Na^+. As shown in the table, the processes that contain Na^+ have no mass load, because there is no transfer of constituent. Na^+_{in} is equal to Na^+_{out}. Therefore optimization with the composite curve is not possible and also not necessary. The network with Na^+ could easily be designed by checking every brewery process effluent. If the $Na_i^{+\ lim,out}$ is lower than the $Na^{+\ lim,in}$ of the orange orchard, redirection is possible. In the case of El Obour process 1, 2, 3, 7, 11, 12, 13, 14, 15, 16, and 17 met this requirement and were sent to the orange orchard. As the total sum of these processes is lower than the required water flowrate for the orange orchard, no internal recirculation options were possible. The network that was designed could be found in Appendix 4b, Figure 25. The total flowrate that is required to satisfy the total network was 14641 m^3/month. The fresh water flowrate of the brewery was not reduced because no internal recirculation was possible. The wastewater production of the brewery was decreased with 51% to 4804 m^3/month. The remaining wastewater flowrate was send to the orange orchard. This was a total 4951 m^3/month from process 1, 2, 3, 7, 11, 12, 13, 14, 15, 16, and 17. Accordingly, the network with Na^+ as limiting constituent is 51% circular* on water.

Table 19: Process characteristics of El Obour brewery. Per key process the water flowrate and Na^+ concentration limits are shown.

No.	Process	f_i [m^3/month]	$Na_i^{+\,lim,in}$ [mg/L]	$Na_i^{+\,lim,out}$ [mg/L]	Δm_i [kg/month]
1	CO_2 washer	596	0	0	0
2	Boilers	75	0	0	0
3	Cooling towers	1137	0	0	0
4	CIP brew house	709	11719	11719	0
5	CIP wort copper	213	11719	11719	0
6	CIP wort cooler	993	11719	11719	0
7	BMF and PVPP air removal	142	0	0	0
8	CIP Cellars	1419	11719	11719	0
9	Crate washer	93	4073	4073	0
10	Bottle washer	885	6453	6453	0
11	Bottle filler	259	0	0	0
12	Vacuum pump	853	0	0	0
13	Bottle pasteurizer	1146	0	0	0
14	Conveyor belt smoother	256	0	0	0
15	Can filler	169	0	0	0
16	Can rinser	169	0	0	0
17	Can pasteurizer	184	0	0	0
18	Keg washer	457	12508	12508	0
20	Orange plant	9836	70	13000	127180

4.5.3. Total N as limiting constituent El Obour

For Total N the composite curve could be constructed because there was mass transfer. Figure 18 shows the composite curve for Total N as limiting constituent. The table for construction the composite curve with intervals, Total N limiting concentrations, flowrates and cumulative mass load can be found in Table 28 and Table 29, Appendix 4c. The pinch concentration was 100 mg/L at a cumulative mass load of 692 kg/month, as shown in Figure 18. The minimum required fresh water flowrate to satisfy this network with Total N as limiting constituent is 7209 m^3/month.

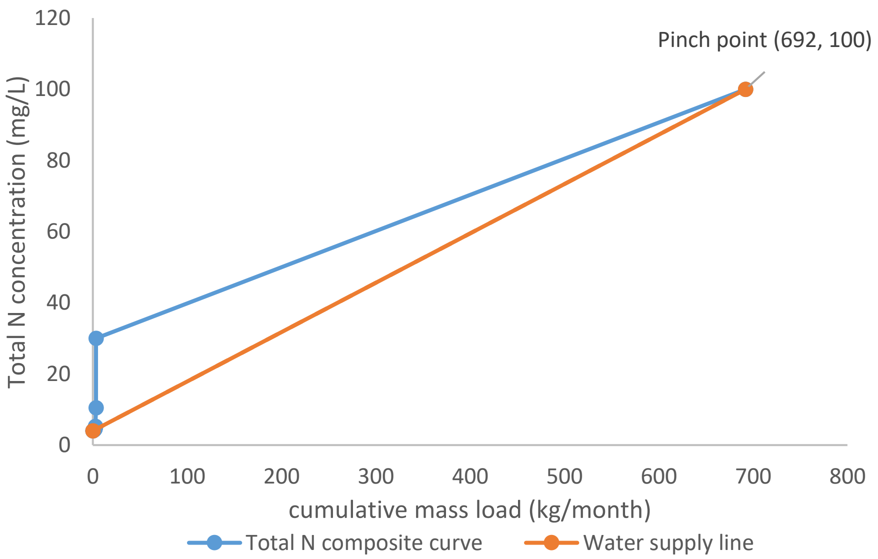

Figure 18: Composite curve for Total N as limiting constituent for El Obour brewery with actual process water flowrates. Based on data from Table 28 and Table 29. The blue line shows the composite curve and the orange line is the fresh water supply line. The pinch point is the point where the water supply line touches the composite curve.

Figure 18 shows that the pinch point is located at the end of the composite curve. This means that there is actually no separation of sinks and sources based on the water flowrates available and transferred mass. It shows that if this network was one single water using process, the network could only be satisfied with fresh water. The network design would look like the initial network from section 4.4. However, there is one requirement for the design of the network and that is that the orange orchard is always considered as a sink. Process effluents that comply with the concentration restrictions of the orange orchard, should be sent to the orange orchard at any time. As Table 28 from Appendix 4c shows, every brewery Total N process effluent concentration is lower than the maximum allowable influent concentration for the orange orchard. Therefore, every brewery process effluent could be sent to the orange orchard.

Figure 26 from Appendix 4c shows the integrated network for Total N as limiting constituent. All the brewery processes require fresh water as influent, so there is no saving in fresh water intake in the brewery itself. The brewery wastewater production was reduced to 0 m^3/month because everything is sent to the orange orchard. This was not enough to fulfil the demand of the orange orchard thus an extra 80 m^3 fresh water per month was required. However, this brewery network based on Total N as limiting constituent is 100% circular* on water.

4.5.4. Reference constituent and integrated design

The previous section shows for the three key constituents the composite curves and constituent network for the El Obour brewery with actual process water flowrates. According to these calculations, the fresh water consumption for COD, Na^+ and Total N is respectively, 15930 m^3/month, 14641 m^3/month and 9836 m^3/month. The COD network, see Figure 17, has the highest fresh water consumption and was therefore chosen as reference constituent for the final integrated network.

The next step was to check if the redirected streams in the COD network were also possible conform the other constituent limitations. For every sink in the COD network that received effluent water from a source, the Na^+ and Total N maximum allowable influent concentrations were compared to the source effluent concentration. Table 20 shows the sinks from the COD network from Figure 17 and their initial sources. Table 21 shows the characteristics of the sources used.

Table 20: Sinks from network with COD as limiting constituent, corresponding maximum allowable influent concentrations for Na^+ and Total N and the initial source from the network design from Figure 17

Process No.	Sink	$COD_{lim,in}$ [mg/L]	f_i [m^3/month]	$Na^+_{lim,in}$ [mg/L]	Total $N_{lim,in}$ [mg/L]	Input source [no.]
20	Orange plant	120	9836	70	30	1, 2, 4, 6, 7, 16
10	Bottle washer	200	885	6453	4	3
9	Crate washer	250	93	4073	4	3

Table 21: Sources for the sinks used in the COD network from Figure 17 with corresponding maximum allowable influent concentrations for Na^+ and Total N

Process No.	Sink	f_i [m^3/month]	$COD_{lim,out}$ [mg/L]	$Na^+_{lim,out}$ [mg/L]	Total $N_{lim,out}$ [mg/L]
3	Cooling towers	1137	150	0	4.00
16	Can rinser	169	32	0	4.00
7	BMF and PVPP air removal	142	27	0	5.71
4	CIP brew house	709	8	11719	4.10
6	CIP wort cooler	993	8	11719	4.07
1	CO_2 washer	596	0	0	4.00
2	Boilers	75	0	0	4.00

Based on the information of Table 20 and Table 21 the integrated network could be designed. For the orange orchard, Na^+ was the limiting constituent and thus source 4 and 6 could not be reused by this sink. This resulted in a higher fresh water flowrate of the total network. Also shown in Table 20 and Table 21, Total N caused no restriction for any of the processes. Total N was therefore considered as a non-limiting constituent that should not be taken into account when constructing the integrated networks. The brewery fresh water flowrate did not change compared to the COD limiting constituent network. The total wastewater production of the brewery increased due to the fact that source 4 and 6 could not be reused by the orange orchard. Accordingly, the circularity* decreased as well. Figure 19 shows the integrated network satisfying all three constituent requirements.

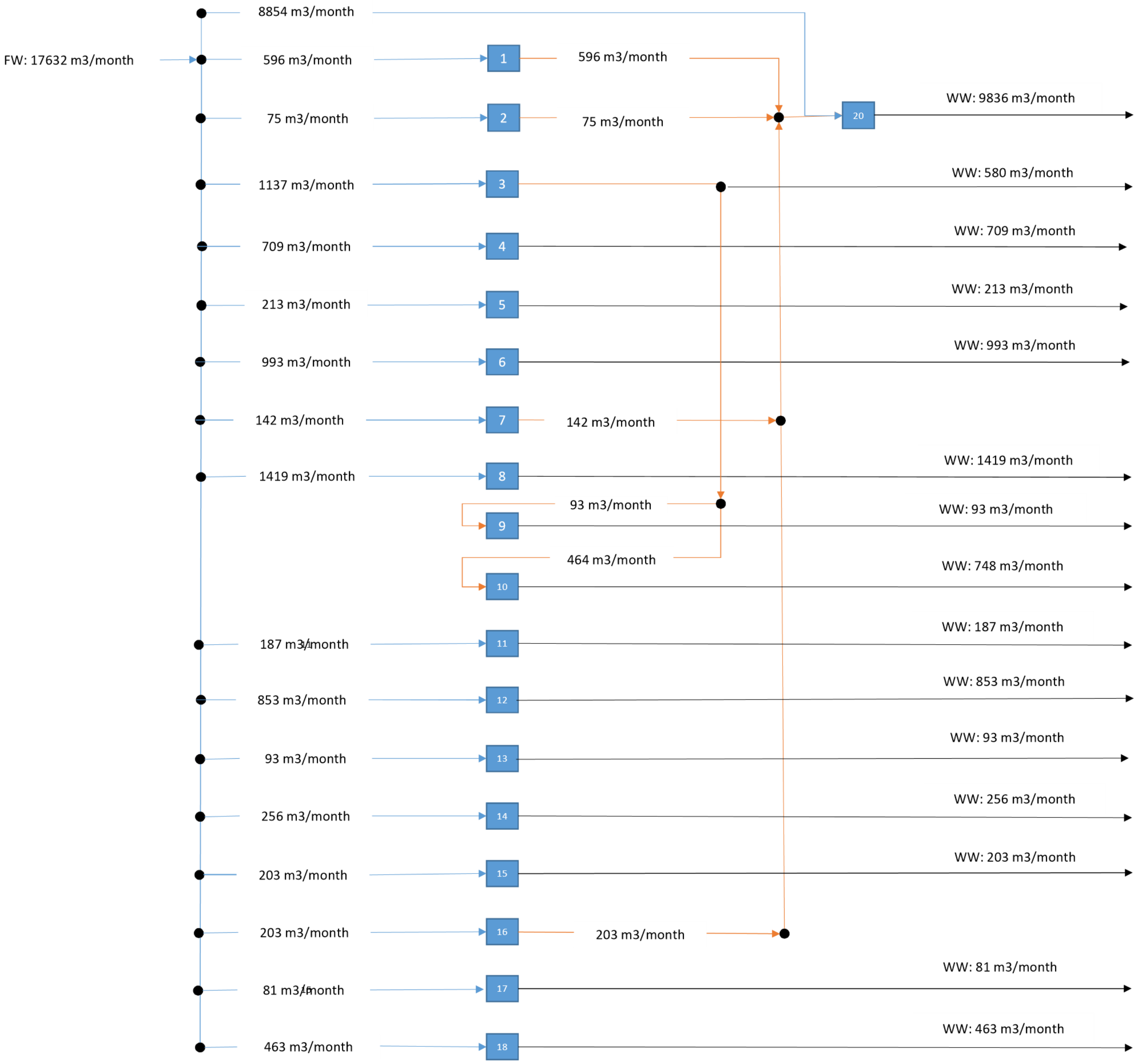

Figure 19: Integrated network for the El Obour brewery based on the three key constituents COD, Na+ and Total N. The brewery is 11% circular on water. Process 1 till 18 refer to the process numbers in Table 11. Process 20 is the external user, the orange orchard. Blue lines indicate fresh water inflow; orange lines indicate recirculation streams and black lines refer to wastewater sent to the WWTP.*

The network in Figure 19 had a fresh water flowrate of 8777 m^3/month in the brewery. This is slightly lower than the initial water flowrate due to the recirculation of process effluent from process 3 to process 9 and 10. The wastewater production of the brewery had decreased with 20% to 7795 m^3/month. 982 m^3/month from this was sent to the orange orchard and thus the brewery in the integrated network complying to the three key constituents and COD as reference constituent was 11% circular* on water.

4.6. El Obour water pinch – UBM

The steps from section 4.5 were now applied to construct an integrated network with the UBM process water flowrates of El Obour brewery. Constituent concentrations changed slightly and the water flowrates of the processes with a UBM values changed as well, see Appendix 1 Table 23. For the processes without an UBM value the actual water flowrate was used. The initial fresh water flowrate for the El Obour brewery is in this case 8466 m^3/month and for the full network 18302 m^3/month. Because the constituent concentrations stayed more or less the same, COD was still the reference constituent. Besides, Total N had no restrictions and was considered as a non-limiting constituent. However, due to a change in water flowrate for some processes, the circularity* increased to 13%, 1016 m^3/month was sent to the orange orchard. Figure 27 in appendix 4d shows the integrated network for El Obour with UBM values.

4.7. Sharkia water pinch – Actual and UBM

For the Sharkia brewery the water pinch was applied in the same way as described in section 4.5 for the El Obour brewery. Process 1 through 17 refer to the brewery processes, listed in Table 12. Process 20 is again an orange orchard, the external user, with characteristics from Table 9.

The integrated networks for the Sharkia brewery with actual process water flowrates and UBM process water flowrates are shown in Figure 28 and Figure 29 Appendix 5. Here also COD was the main limiting constituent thus the COD network served as the reference network for the integrated network. Total N caused no restrictions at all and was not considered as a limiting constituent.

For both networks the same process effluents could be sent to the orange orchard, namely process 1, 9, 12, 14, 15, 16 and 17. The network with actual process water flowrates resulted in a circularity* of 24% with 3763 m^3/month sent to the orange orchard. The network with the UBM process water flowrates resulted in a brewery that is 34% circular* on water. Here 5064 m^3/month was sent to the orange orchard.

4.8. Overview results of two case breweries

Table 22 shows an overview of the results for the fresh and wastewater flowrates in the brewery of El Obour and Sharkia. Also the circularity* per network is given.

Table 22: Overview of results for Sharkia and El Obour

		FW_{new} *[m^3/month]*	WW_{new} *[m^3/month]*	***Flow to orange orchard [m^3/month]***	***Circularity* [%]***
El Obour	***Actual***	8777	7795	982	11
	UBM	7909	6607	1016	13
Sharkia	***Actual***	15695	11922	3763	24
	UBM	14961	9827	5065	34

5. Discussion

In this research, the water pinch was used to proof the concept of circularity in a water network with a brewery and orange orchard. With the help of this method the initial degree of circularity of a brewery and an orange orchard could be determined, without treatment of process effluents. Besides, this results show that the water pinch can be applied to any multi-user water network to increase circularity, as long as characteristics of water quality requirements are known.

In this discussion section first a practical interpretation of the results is given. Then the method used is discussed. This is followed by a discussion of the major and minor findings of this report in the context of published literature.

5.1. Practical interpretation of the results

Up to now, there are no examples found in literature of a network with a brewery in combination with an external user optimized with the water pinch. Feng et al. (2009) achieved 8% reduction in fresh water consumption and 13% reduction of wastewater in a single brewery network. Oliver et al. (2008) showed a fresh water reduction of 30.22% by using the water pinch in a winery network. Although the last one was a winery, the processes used were comparable to the brewery processes in this work. Both researches show reductions below 50%. The results obtained with the water pinch for the El Obour brewery and Sharkia brewery showed reductions of fresh water and wastewater production also lower than 100%. However, the work of Feng et al. (2009) and Oliver et al. (2008) was not focussing on circularity; no external user was present. Besides, conditions and data differ from case to case. This makes it difficult to compare the specific water savings and circularity results found in this work to other work with the water pinch. Therefore, in this section a practical interpretation of the circularity* numbers found was given. The bottlenecks in the breweries were discussed and possible solutions to increase circularity were addressed.

5.1.1. COD impact

COD is for the majority of the processes in both breweries the limiting constituent. Organics present in the process effluents determine the COD concentration. In the CIP effluents from the wort copper and cellars department, the COD value is high due to yeast rest, hop and other beer ingredients (see Table 11 and Table 12). This concentration COD is more or less stable because these processes form the basis for beer. These streams will always contain high COD values. A direct reuse of these streams by an orange orchard will not be possible without treatment as the COD concentration is far above the limit.

In the packaging department, the COD concentrations are more susceptible to fluctuations than in the CIP effluents. In the bottle washer, crate washer and keg washer external organics enter the processes and end up in the process effluent effecting the COD concentration (see Table 11 and Table 12). Especially the returnable bottles can contain high concentrations of microorganisms, organic compounds, glue of the labels, the labels itself and other filthiness. Nonetheless, the concentration COD is highly dependent on the local conditions. Big discrepancies can occur and this means that in some cases an external user might use the effluent of the returnable packaging lines based on COD concentrations. However, in El Obour the processes that could not be sent to the orange orchard were mainly the processes that do not involve external COD (see Table 17 and Table 18). Table 18 shows that the can pasteurizer, vacuum pump, bottle filler, conveyor lubrication and bottle pasteurizer cannot be reused by the orange orchard. These processes all involve beer and COD is determined by the extract losses. The amount of beer spilled due to breakages of the packaging material in these processes increases the COD effluent concentration significantly. Especially in the can pasteurizer, bottle filler and conveyor lubrication the extract losses of respectively 1%, 1.3% and

1.5% (see Table 25) have a large effect because of the relatively small flowrates. The results show that the circularity potential of a brewery for COD depends mainly on the extract losses. To increase the breweries circularity, based on COD restrictions, the extract losses should be minimized.

5.1.2. Na^+ impact

It is interesting that for both breweries only the CIP brew house and CIP wort cooler effluent have Na^+ as limiting constituent. On beforehand, it was expected that the salt load, and especially Na^+ load, in the process effluents would play a crucial role in the reuse of process effluents. Particularly because oranges are sensitive to sodium toxicity (Ayers & Westcot, 1985). Besides, at places where sodium is used in the brewery the concentration is usually higher than the maximum allowable influent concentration of orange irrigation water. However, after the screening of water use and constituent concentration in the processes of the brewery, it became clear that in both breweries the share of sodium containing process effluents is low. In El Obour only 39% of the process effluents contain sodium, in Sharkia this is 35% of the brewery processes. So for both breweries the majority of process effluents does not contain any sodium. This shows why Na^+ is not the main limiting constituent for the integrated brewery networks.

Nevertheless, some of the process effluents that could not be reused due to restrictions caused by COD had also a Na^+ concentration greater than the orange orchard limit. This is the case for the CIP cellars, CIP wort copper, crate washer and bottle washer in both breweries and the keg washer in the El Obour brewery. As mentioned in section 3.2, all of these processes involve cleaning activities with caustic, NaOH. In both breweries, the NaOH concentration used is at least 2%. Hence, even when the COD concentration decreases for some reason (due to decreasing extract losses or fluctuations in external COD), Na^+ will become the limiting constituent. Unless the use of caustic changes in the cleaning process, the effluents in these processes could never be sent to the orange orchard. For the El Obour brewery with UBM process water flowrates, this means that the circularity* potential drops to a maximum of 45%. In this case, only 3828 m^3/month of the 8466 m^3/month is available for the orange orchard. For Sharkia this potential is a bit higher due to the low amount of returnable bottles as well as the lack of a keg washer. The circularity* potential in Sharkia will be 61% as 9200 m^3/month of the 14961 m^3/month would be available for the orange orchard. Na^+ decreases the circularity* potential significantly in both breweries. Consequently, to increase the circularity of a brewery the processes with caustic should be considered as a bottleneck. Solutions to decrease or remove the use of Na^+ containing chemicals could help to make a brewery more circular on water.

5.1.3. Brewery type differences

Assuming that both breweries operate on the UBM water flowrates, the breweries reached their goals in water efficiency and were ready to implement circularity. This means that the El Obour brewery could be 13% circular* on water and the Sharkia brewery 34% circular* on water (see results in section 4.6 and 4.7). The Sharkia brewery can be more than twice as circular* on water as the El Obour brewery while local conditions are more or less the same (see case description in section 4.1). The difference can be found in the fact that the Sharkia brewery packaging lines are different from the El Obour brewery packaging lines. Sharkia produces 45% of the total volume for PET bottles, 46% for cans and only 11% for returnable glass bottles. El Obour on the other hand puts 57% of the total volume in cans, 26% in returnable bottles and 17% in kegs. As discussed above, returnable product lines produce effluents with high, variable COD values as well as effluent that contains Na^+ due to caustic use. In Sharkia the main products are PET bottles and cans, packaging lines where no caustic is used so Na^+ concentrations are zero. COD concentrations were only dependent on the extract losses and remained low. In El Obour 43% of the packaging materials were returnable. In the bottle washer and keg washer caustic is used to clean and causes high Na^+ concentrations in the effluents, COD is high due to external organics. This is why El Obour has a lower circularity* potential than Sharkia. Returnable product lines involve caustic as well as high, unpredictable COD concentrations and thus these lines are a bottleneck in the circularity on water of a brewery with an orange orchard.

5.1.4. Solutions to increase the circularity in a brewery with an orange orchard

Based on the sections above, the circularity of a brewery and an orange orchard is dependent on several aspects. First, the degree of returnable packaging materials in a brewery is important. The results in this thesis show that the lower the amount of returnable packaging materials, the higher the circularity* potential on water. However, from a sustainability point of view, getting rid of returnable packaging material and switching to one-way packaging is not preferred. Solutions to take out the reuse restricting constituents are therefore more desired. In this section some solutions to reduce the constituent concentrations are discussed to increase the circularity of a brewery.

The restricting constituent, Na^+, can be removed by using alternative cleaning agents for caustic. An alternative for caustic is potassium hydroxide (KOH) (Muthukumaran, et al., 2013). Potassium hydroxide is a similar cleaning agent but does not contain any sodium. The big advantage of potassium hydroxide is that, instead of sodium, potassium is not harmful for plants or soil. It is even necessary for plants to grow because it enhances the photosynthesis, it activates enzymes and it even helps by the transportation of water in the plants. High amounts of potassium increase the physical health of crops and shelf life of fruits and vegetables (Prajapati & Modi, 2012). The disadvantage for potassium hydroxide is the price. Per kg, potassium hydroxide is almost 6 times more expensive than sodium hydroxide (Diversey, 2019). This is why many industries still use sodium hydroxide instead of potassium hydroxide. Despite the costs, potassium hydroxide is a promising alternative for caustic especially because it reduces the sodium content to zero and thus increasing the reuse opportunities of these process effluents.

Another method to reduce the Na^+ concentration in the process effluents of the CIP streams and the returnable packaging lines, is to collect the caustic streams separately and reuse them multiples times. In this way, the caustic is only sent to the drain after a certain period when it has to be fully refreshed. Between the moment of complete replacement of the caustic solution and the next, the process effluent of these processes contain only traces of caustic, the carry-over, and water. These process effluents can safely be sent to the orange orchard or other external user based on Na^+ concentrations. On the day of caustic replacement, the process effluent is not send to the orange orchard but collected separately. In this way, the circularity can never be 100% but due to the separation of the peak load and the low contaminated streams, the circularity is increased.

To give an example; the bottle washer effluent contains high concentrations of caustic (see Table 11). This concentration caustic is based on the caustic baths in the bottle washer that were sent to the drain in combination with the rinsing baths. However, when the caustic bath effluent is collected separately, the rinsing water effluent would only contain traces of caustic due to the carry over. This carry over is not quantified in the Heineken breweries. The rinsing water effluent might be a possible sources for the orange orchard when carry overs are not too high. The separate caustic bath effluent could be reused multiple times before discharging it to the drain. This effluent could never be used for the orange orchard without treatment.

The other restricting constituent for the CIP process effluents and returnable packaging processes, is COD. COD is an issue in many industries and has therefore many treatment applications. The main treatment to reduce the organic load is to use biological treatment in the form of anaerobic-aerobic treatment. Most of the breweries these days have an anaerobic-aerobic wastewater treatment facility on site to treat all their process effluents. However, this thesis shows that it is not necessary to treat every process effluent. Therefore, the CIP process effluents, the crate washer effluent, bottle washer effluent and keg washer effluent should be collected separately. In this way, the process effluents with low COD values are not contaminated. The process effluents with a high organic load were send to an anaerobic-aerobic treatment facility and then send to the orange orchard. Examples of anaerobic treatment systems are; UASB (Upflow Anaerobic Sludge Blanket), CSTR reactors (Continuous Stirred Tank Reactors), EGSB (Expanded Granular Sludge Bed) and anaerobic filters (Chan, Chong, Law, & Hassell, 2009). UASB and EGSB are widely applied in breweries in combination with an aerobic lagoon tank or activated sludge tank (Driessen & Vereijken, 2003). Aerobic systems have an average COD removal of 90-98% and anaerobic systems up to 70-85%. This means that the COD levels of the CIP process and returnable packaging lines will decrease sufficiently to comply with the orange orchard restriction level. With an anaerobic-aerobic treatment step the process effluents that could not be reused before due to COD restrictions, can now be reused and circularity is increased.

Figure 20 shows a schematic overview of the possible steps to increase the circularity of a brewery and an orange orchard based on the results of the case studies in this thesis. Based on the flowchart both breweries could become 100% circular on water when implementing an anaerobic-aerobic treatment facility and replace all NaOH with KOH.

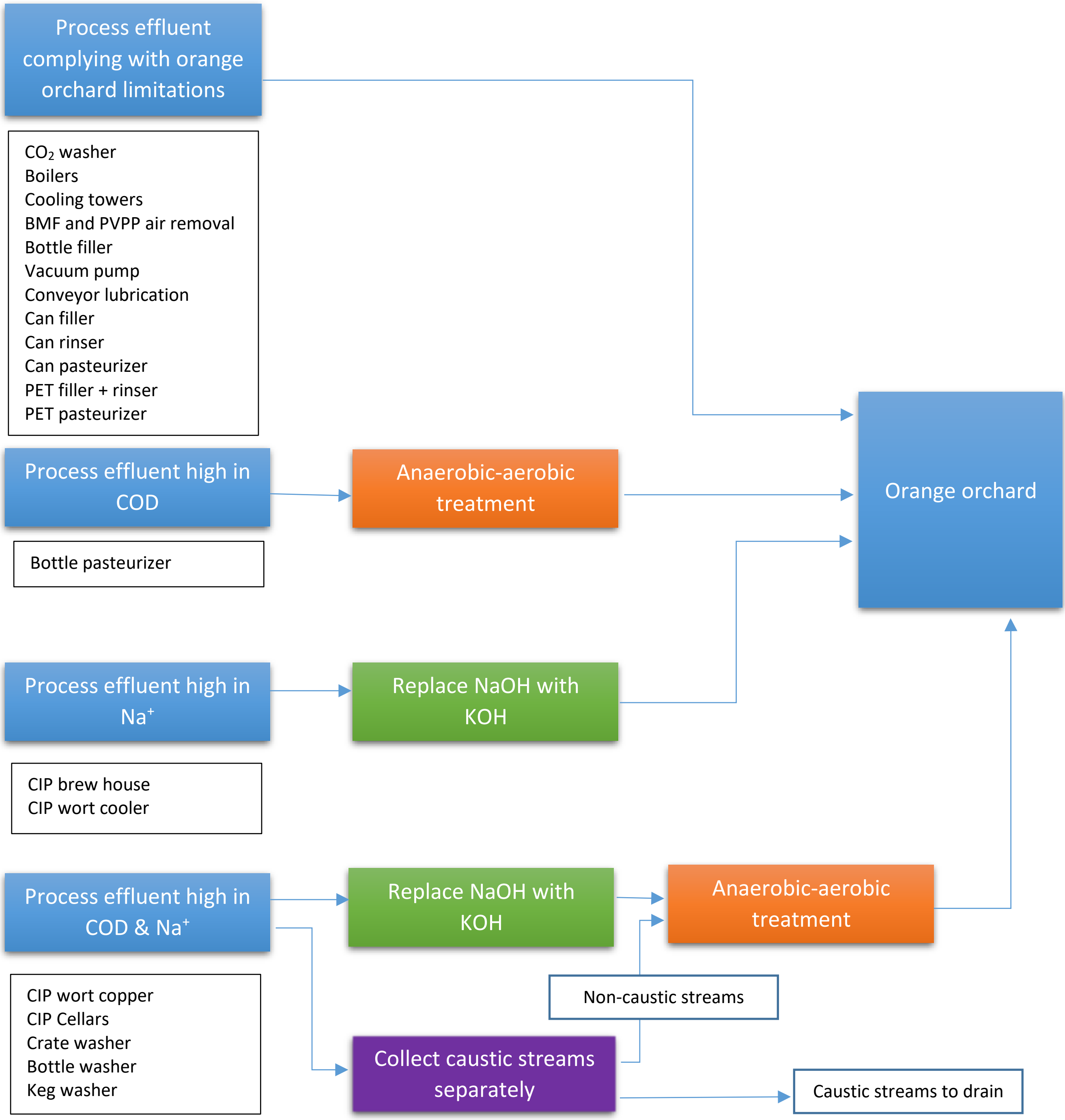

Figure 20: Schematic flowchart to demonstrate the opportunities to increase the circularity on water of a brewery and orange orchard.

5.2. Method

In this section the specific method used in this thesis to obtain the results is discussed.

5.2.1. Single constituent approach

In this research the single constituent approach of the water pinch was applied. In the single constituent approach, the composite curve is constructed for every single constituent. Per constituent a network is designed and the final, integrated network is constructed by checking the redirected streams of the reference constituent and the other constituent requirements. Considered is that the constituents do not interfere with each other. However, in practise the constituent transfer happens simultaneously in a stream. COD and Na^+ were both transferred in the same processes. Assuming that the reference constituent results in the most optimized network is not always the case. Wang and Smith (1994) concluded that the single constituent approach is not always applicable to a multi-constituent network. They showed with an example that the minimum water flowrate for a network with constituent A and B is neither the water flowrate calculated with constituent A as key constituent nor the minimum water flowrate calculated with constituent B as limiting constituent. By assuming that there is a certain relationship between the transfer of constituent A and B, the composite curve for both constituents was made and the minimum water flowrate was calculated. This is called the multi-constituent approach. To create this multi-constituent approach, Wang and Smith (1994) shifted the in- and outlet concentrations of the constituents. To reuse water from process 1 for process 2, the effluent constituent concentration of process 1 had to be lowered for process B as it did not meet the influent requirements. But as process A and process B were connected, the effluent concentration of constituent A had to be lowered as well. Accordingly, the effluent of process 1 had to be intercepted when the constituent concentration B reached its maximum allowable effluent concentration for process 2. The concentration of constituent A was at that moment lower than the maximum effluent concentration.

In practise this would mean that during the contamination of a process stream, the stream could be intercepted before the actual maximum effluent concentration was reached. This is not possible in the brewery processes as these are processes with a fixed in- and effluent concentration. The multi-constituent approach of Wang and Smith (1994) is therefore not applicable to the case studies in this work. The single constituent approach is valid here.

5.2.2. Quantitative data

The data used in this work are mainly average measured values and even some estimations. For the sake of this research, this was sufficient to give a rough indication of the circularity of the case breweries. Certainly because it showed the opportunities of the water pinch in a circularity perspective as well as the brewery specific opportunities. However, some of the data used in this work could be questioned despite the fact that discrepancies can occur.

First of all, the data for the CIP processes is based on an average CIP procedure where all the cleaning steps were combined as it was one process effluent. In practise, the CIP procedures have several phases, first a water rinse, then caustic pulses and then again a water rinse (see Table 3 and Table 4 for an example CIP procedure). In this research the separate flows were combined and modelled as one flow containing water with caustic and/or acid. This was done because only a combined water consumption for the complete CIP procedure was measured in both breweries. The sodium concentration, based on the caustic solution used during CIP was assumed to be present in the combined stream as well. However, in practise the caustic solution is a separate stream and thus would the caustic concentration in the combined stream be lower as it is diluted with the rinsing water. This was not taken into account in this research as there was not enough measured data available at that time.

Another discussion point is the fact that the amount of water used in the CIP is dependent on the amount of batches in the brewery. This cannot be seen from the average measure data used in this work. The caustic solution used in the CIP procedures is in some breweries recirculated and used multiple times. From the brewery in Zoeterwoude it is known that every caustic solution for one cleaning is used twice before it is sent to the drain (Schaap, 2019). This would imply that at one moment the CIP effluent is low in caustic and in the other moment caustic concentration is high because a complete caustic tank is sent to the drain. As the brewery process is also a batch process, the amount of CIPs is highly dependent on the amount of different brews. Therefore, the water flowrate of the CIP procedures is very uncertain and can cause big discrepancies.

The big variation in water flowrate and caustic concentration can also be found in the bottle washer. The water flowrate used in this work is based on the average water consumption per month. The sodium concentration is based on the caustic consumption used per month. However, a bottle washer has no continuous in- and outflow. The bottle washer is also a batch process. Almost for every brewery, the bottle washer is filled and after a certain period of time the complete caustic bath is refreshed. This means that in the period between filling and refreshing only carry-over caustic is flowing to the drain. In the majority of time, the bottle washer effluent is not high in sodium. Solely at the day of complete refreshing, there is a peak load. Consequently, it might be possible that the majority of the bottle washer effluent could be sent to the orange orchard as the Na^+ concentration is not so high. This was not considered in this work because there was not enough data to verify the concentration changes.

Besides the variation in CIP and bottle washer water flowrates as well as Na^+ concentrations, the overall water consumption in a brewery is susceptible to seasonal variations. In summer, more beer is produced than in winter, thus more water is consumed, and more water is available for the external user. The data obtained from El Obour is average monthly data from 1.5 years and can be considered as average. However, the data for the Sharkia brewery is only from one month, seasonal variations were not included. This problem could be mitigated by gathering data from more months or introduce a seasonal factor.

Lastly, the estimated maximum allowable influent concentrations of the brewery processes could be questioned. In a brewery the quality of the influent water is drinking water quality with some extra requirements (see Table 5). This means that the influent concentration of the key constituents is 0 mg/L for COD and Na^+ and 4 mg/L for Total N. Consequently, no internal reuse is possible because the influent concentration limit is too strict. This would mean that the water pinch could not identify possible sinks and sources in the brewery as every process requires fresh water. To be able to apply the water pinch on a brewery with the chance of internal recirculation, some of the influent concentrations were increased. Estimations were made based on knowledge and experience of Heineken employees. In this way, some of the COD influent concentrations were increased to an acceptable level. This accounts for the cooling tower, the bottle washer, vacuum pump, bottle pasteurizer, conveyor lubrication and can line. Because the influent concentration did increase, the effluent concentration increased as well. Therefore, the estimated maximum allowable influent concentrations determined the circularity* potential of the process. For the processes in the returnable bottle line this was a minor impact as external factors influenced the effluent COD concentration. However, for the cooling tower, vacuum pump, conveyor lubrication and can line processes, the circularity* potential might be higher than estimated in this research. For example the cooling tower has an actual COD influent concentration of 0 mg/L, in the water pinch the concentration was increased to 150 mg/L. No extra COD is added to this streams so the effluent concentration is equal to the influent concentration. Consequently, in this research the cooling tower effluent could not be reused by the orange orchard, as the influent limit was 120 mg/L. Nevertheless, in the actual case of 0 mg/L the cooling tower effluent could be sent to the orange orchard and the circularity* of the brewery would increase. In this research the choice was made to use maximum allowable influent concentrations in the water pinch. This resulted in opportunities for internal recirculation as well as external recirculation. If only the actual potential of the two case breweries was desired, a water pinch with actual constituents concentrations should be done.

The overall conclusion from this discussion section is that it is important to have good data. To draw specific conclusions about reuse and circularity potential of a brewery the level of detail is very important. The higher the level of detailed data, the more specific conclusions and solutions could be found from the water pinch.

5.2.3. Network design

The method to design the networks in this work is based on the guidelines of Brouckaert et al. (2005). This method originates from the work of El-Halwagi and Manousiousthakis (1989) and Wang and Smith (1994) who developed the water pinch analysis and network design methods. Brouckaert et al. (2005) made a stepwise method that was more easily followed than the explanation given by El-Halwagi and Manousiousthakis (1989). Although many other researchers used this method, the objective was never to design a network focussing on circularity. In other work, the water pinch is used to optimize a network and reduce the fresh water and wastewater flowrates. Every process is of the same importance, none of the processes is more important to satisfy first, the selection is only made on available water flowrate and constituent concentration. However, in this work to force circularity the external user was indicated as the most important sink that should be satisfied first. Therefore, it could happen that internal sinks could not be satisfied because the orange orchard used already all the sources. This happened for example in the case of the El Obour brewery network design with COD as limiting constituent. Here, brewery processes 5 and 8, marked as sinks, could not be satisfied because they had a maximum allowable influent COD concentration of 0 mg/L and the orange orchard took all the sources that met this requirement. Accordingly, the internal recirculation was lower than expected if one followed the regular water pinch network design strategy. For the El Obour network with COD as limiting constituent the fresh water savings of the brewery were in this work only 7% but if every sink was of the same importance the savings inside the brewery could be 15%, almost double. The drawback is that the circularity* decreases in this case to 28% compared to 31%. Therefore, the objective of the research is very important. To increase circularity the method applied in this research is beneficial. Nevertheless, if the internal efficiency is also important it might be better to assign every sink with the same importance.

Another discussion point is that in the network design method of this work, no combination of streams to achieve the concentration requirements were allowed. In most network designs of fixed flowrate problems, dilution of rich streams with lean streams is used to achieve the concentration requirements. In this way more water can be reused. The water pinch is developed to simplify the network to a single water-using process and thus dilution of streams is possible. The theoretical fresh water flowrate, calculated with the composite curve, assumes that every stream could be diluted with another stream to reach a certain concentration. However, because of the complexity of the network (17 and 18 brewery processes) and only manual calculations, the dilution of streams was excluded in this network design. This simplified the construction of the networks and explained the difference in fresh water flowrate calculated by the water pinch and the actual water flowrate in the designed networks. Besides, from a practical perspective it is not recommended to have multiple connections between streams. A lot of transportation pipes and connections would be necessary.

Due to this increased complexity, the chance for failure or incidents will increase as well. Therefore, the choice to exclude dilution possibilities is recommended.

The last discussion point is the impact of reference constituent. For both breweries, COD was used as reference constituent to design the integrated networks. This was based on the criteria that the reference constituent is the constituent that gave the highest minimum fresh water flowrate. In this case the network with the most restrictions is used as basis. However, to check whether or not it matters if COD was chosen as reference constituent, another integrated network was designed with Na^+ as reference constituent. Total N was not used as reference constituent because it is for none of the brewery processes limiting.

For both breweries, the only sink in the networks with Na^+ as limiting constituent, was the orange orchard. Process effluent 1, 2, 7 and 16 were the sources. The COD process effluent concentrations of these sources were compared to the maximum allowable influent COD concentration of the orange orchard. The sources that did not comply to this limit were no longer sent to the orange orchard and had no destination within the network. For both breweries this resulted in a network that was almost similar to the integrated network with COD as reference constituent. The only difference was that the internal redirected streams in the COD integrated network were not present in the Na^+ integrated network. In the COD integrated network of the El Obour brewery the effluent from process 3 was sent to process 9 and 10. In the Na^+ reference integrated network, process 3 was completely sent to the WWTP because it could not be used by the orange orchard due to COD restrictions. For Sharkia only the reuse of effluent from process 2 by process 7 was not present in the Na^+ reference integrated network. Hence, the choice of reference constituent does not have a major impact on the integrated network design. Especially from a circularity point of view, there is no difference and it does not matter in what way the network is designed. For both reference constituents, the same process effluents were sent to the orange orchard. However, the integrated network with COD as reference constituent, showed more opportunities of reuse inside the brewery. It showed not only circularity opportunities but also water efficiency possibilities.

5.2.4. Difference between UBM and actual process water flowrate networks

As mentioned before, the UBM values for Heineken were set for every brewery to define best practise values. When a brewery reaches the UBM process water flowrates, the brewery performs in optimal conditions, in the most water efficient way. The results from the water pinch applied to El Obour and Sharkia show no difference in network lay out between the network with actual process water flowrates and the network with UBM process water flowrates. The same process effluents go to the orange orchard as well as the same recirculation connections in the brewery between process 3 and process 9 and 10 for El Obour and between process 2 and 7 for Sharkia.

For both breweries stands that the circularity* is higher for the integrated networks generated with the UBM process water flowrates. Even though the network layouts were the same, the circularity* is somewhat higher. The reason for this is that at UBM water flowrates the brewery produces at its best practise value and processes perform in the most efficient way for this specific location. However, the UBM process water flowrates are only available for the packaging department and general CIP procedures (see Table 11 and Table 12). The processes as cooling tower, boilers and more specific CIP processes (CIP wort copper and CIP wort cooler) had no UBM and kept their actual water flowrate. Only the processes with a change in water flowrate determines the change in circularity. For the El Obour brewery the UBM water flowrate for process 16 is higher than the actual water flowrate. More water is available for the orange orchard despite the fact that the overall fresh water flowrate decreased. The change in circularity is however not significant and thus for the El Obour brewery both UBM and actual process water flowrates could be used.

For the Sharkia brewery the change is bigger, the circularity* increased with 6% for the UBM integrated network. This change is due to the fact that the total water flowrate, that was redirected to the orange orchard, increased with 1328 m^3/month. For Sharkia five process out of nine from the packaging department could be sent to the orange orchard and all of those had an UBM value. This would mean that the overall efficiency for those processes was better in the actual situation than recommended by the UBM. However, the data obtained from the Sharkia brewery was not average data, it was only data from one month. Consequently, the UBM process water flowrates would give a better estimation of the process water flowrates and thus of the circularity* potential in the brewery.

5.3. Findings in the context of published literature

The most important result of this study is that the water pinch could be applied to a multi-user water network consisting of a brewery and orange orchard to achieve circularity. The results show that it is possible to achieve circularity by modelling the brewery and orange orchard as a single water-using process. Without changing the initial effluent quality of the brewery processes, the El Obour brewery could be 13% circular* on water and the Sharkia brewery 34%. These results were obtained by switching the focus of the water pinch from a water efficiency point of view towards a circularity point of view. Instead of internal reuse connections, the connections between the brewery and external user were made first. In this section the circularity results were placed in the context of published literature to show similarities and differences.

5.3.1. Water pinch framework

In earlier research the water pinch was used to decrease the fresh water consumption and wastewater production within a process plant. For example the researches of Xiao and Cai (2017), Balla et al. (2018) and Skouteris et al. (2018), all focus on one specific industry and apply the water pinch to optimize the water use. Since the rising concerns about fresh water resources, the framework of the water pinch has been extended from a single process plant to complete eco-industrial parks. Somoza-Tornos et al. (2019) developed a model based on the water pinch that identified the reuse opportunities of a network with ten different industries. Their research is consistent with the findings in this report that the water pinch could be used to increase circularity within a multi-user water network. However, the difference is that the starting point of Somoza-Tornos et al. (2019) is only one source. The source is a wastewater stream from all the industries in the network combined. This is a fundamental difference because the wastewater quality is in this case determined by the most polluted stream. Treatment is always necessary before the water can be reused as influent for one of the network users. It is more an end-of-pipe solution focussing on regeneration of water to achieve circularity. In this research multiple sources were identified and redirected to one external sink and multiple internal sinks without treatment. This was possible because process effluents were not mixed and thus no dilution or contamination by other effluents took place. Instead of adapting the source water with treatment steps to the requirements of the next users, matches were made between sources and sinks based on both quality characteristics and requirements. The advantage is that it shows the opportunities of circularity within the quality range that is already present, instead of changing the source water at all costs to meet the external user requirements. The drawback of this approach is that it can become very complex when the network becomes bigger and more process effluents or external users were added. Modelling in the way as done in this research will be difficult and other ways of modelling should be discovered.

5.3.2. Water pinch and heat pinch

The switch from an efficiency point of view towards circularity was made earlier for energy. The heat pinch is the oldest example of pinch analysis and was developed by Linnhoff et al. (1982) (1983). Already in 2000, Bagajewicz and Rodera (2000) used the heat pinch in a multi plant network to distribute heat. The heat pinch formed the base for the linear program and mixed integer non-linear program that was developed to model the heat exchanges between different industry plants. Bagajewicz and Rodera (2000) showed that it is possible to model the heat transfer between multiple plants by knowing the temperature of the streams and desired conditions. They targeted the heat integration in the entire system as it was one network. After that, the savings per plant could be determined. This is similar to the water pinch applied in this thesis, where the brewery and orange orchard were modelled as one single process.

More recently, Hiete et al. (2012) used the thermal pinch to optimize the cost savings between three different industry plants, a pulp producer, a bio-oil production company and a fibreboard producer for wood waste upgrading. Identical to this work, the heating and cooling demands and sources were identified of the relevant processes for energy integration. A heat integration network could be designed. They extended this optimization with another method, the game theory method, to analyse costs and costs savings in the system. This was used to create trust between the different users, which they say, is necessary to achieve long-term commitment (Hiete, Ludwig, & Schultmann, 2012). The approach is a bit different from the approach in this work, but the similarity is that the pinch analysis is applicable to a multi-user network for both heat and water. This suggests that it can also be applied for different material flows.

The research of Hiete et al. (2012) and Bagajewicz and Rodera (2000) show the potential of the heat pinch and in particular for a multi-user network. However, Boix et al. (2015) found out that there are relatively few studies that deal with the energy management in a multi-user network through mathematical optimization. The reason they gave is that it is difficult to obtain reliable data from the participating users. This touches upon the same problem as encountered in this work, data gathering is difficult. Moreover, to get a good result data is the key. Reliable data is hard to collect, especially when multiple actors were involved. Trust issues among the users and/or practical lack of data cause problems to create a circular network on whatever kind of utility or material.

6. Conclusions and recommendations

6.1. Conclusions

In this chapter the major findings based on the case study research and literature context were summarized. With the help of the formulated six sub-questions, the main research question could be answered. The main research question reads:

Can the water pinch be used to determine if a brewery in a water stressed area can be 100% circular on water, by reusing process effluent from the brewery by external users?

The sub-questions were formulated as:

1. *What is the quality of the individual water streams inside a specific brewery?*
2. *What are the influent water characteristics of agricultural external users around the brewery?*
3. *What is the quality gap between the water streams from the brewery and the influent water for external parties?*
4. *Will this method used, to reuse water, cause 100% circularity on water when implemented in a brewery close to their external user?*
5. *Can the water pinch method, as used for the case breweries, be applied to every brewery?*
6. *How can the quality gap be closed between the water streams from the brewery and the desired water quality?*

Every sub-question is answered below to highlight the conclusions that were drawn in this report.

What is the quality of the individual water streams inside a specific brewery?

The first two sub-questions helped to scope the framework of data needed for the water pinch. In a brewery two types of water can be identified, water used as ingredient and water used as utility. The water used as ingredient is not of interest for the circularity aspect, only the processes that use water as utility were taken into account. Two case breweries were selected to apply the water pinch on, El Obour brewery and Sharkia brewery. Both located in Egypt. For the two case breweries, El Obour and Sharkia, the CIP processes in the brew house and cellars and the processes in packaging and utility department were the key processes used for the water pinch. The initial fresh water flowrate of the breweries as well as the wastewater production was respectively, 9755 m^3/month and 15695 m^3/month with actual process water flowrates and 8466 m^3/month and 14961 m^3/month with UBM process water flowrates. From the characteristics of these key processes, COD, Na^+ and Total N were selected as key constituents.

What are the influent water characteristics of agricultural external users around the brewery?

Based on the google maps location of the breweries, an orange orchard nearby was identified as external user. This orange orchard was estimated to be 87 ha with a water demand of 9836 m^3/month. From literature it became clear that oranges are sensitive to sodium toxicity. Therefore, sodium was highlighted as key constituent for the external user. Due to a limited amount of available data in the brewery the only constituents used in the water pinch were COD, Na^+ and Total N. Nevertheless, these key constituents were considered as representative for the water quality of the brewery streams.

What is the quality gap between the water streams from the brewery and the influent water for external parties?

With the water pinch the networks of the breweries and orange orchard were optimized. Per brewery the effluent COD, Na^+ and Total N concentrations were compared to the maximum allowable influent concentrations of the orange orchard. Every process effluent that complied with these constituent concentrations was sent to the orange orchard. The identification of sinks and sources in the breweries showed the quality gap between the process effluents of brewery and the orange orchard. The majority of the processes were limited in reuse by the concentration of COD. The quality of the effluent of the processes that involved beer such as the can pasteurizer, bottle filler, conveyor lubrication and bottle pasteurizer was not high enough to use by the orange orchard without treatment. In addition, the processes that received external COD (bottle washer, keg washer and crate washer) were highly susceptible to discrepancies depending on local conditions. The quality was not good enough to sent to the orange orchard for both breweries. The CIP processes and returnable packaging processes involved large concentrations of caustic, and thus Na^+, that restricted the reuse of these processes by the orange orchard as well.

For both breweries the reference constituent for the integrated network was COD because that network gave the most restrictions in the first place and needed therefore the highest amount of fresh water.

Will this method used, to reuse water, cause 100% circularity on water when implemented in a brewery close to their external user?

The final integrated networks constructed with the information of the water pinch showed the circularity* potential on water. For El Obour the fresh water consumption decreased with 7% to 7909 m^3/month and the wastewater production decreased with 22% to 6607 m^3/month. The cooling tower effluent could be redirected internally to the crate washer and bottle washer. The process effluents of the CO_2 washer, boilers, BMF and PVPP air removal and can rinser could be sent to the orange orchard resulting in a circularity* of the El Obour brewery of 11 – 13% (depending on the used process water flowrates based on actual measurements or UBM). The fresh water consumption and wastewater production savings for Sharkia were respectively 0% and 34%. No fresh water savings in the brewery were achieved because no internal reuse was possible. Effluent of the boilers, bottle filler, conveyor lubrication, can rinser, can pasteurizer, PET filler and PET pasteurizer could be sent to the orange orchard. The Sharkia brewery could be 28 – 34% circular* on water (depending on the used process water flowrates based on actual measurements or UBM).

For both breweries accounts that 100% circularity* on water cannot be achieved in the current situation where treatment is not allowed. El Obour brewery has a lower circularity potential because the returnable packaging department is larger than in Sharkia. Returnable product lines involves caustic as well as high, unpredictable COD concentrations and thus these lines are a bottleneck in the circularity on water. Na^+ is for both breweries a bottleneck in the reuse of process effluents, it decreases the circularity potential significantly. For the El Obour brewery with UBM process water flowrates, this means that the circularity* potential drops to a maximum of 45%. In this case, only 3828 m^3/month of the 8466 m^3/month is available for the orange orchard. For Sharkia this potential is a bit higher due to the low amount of returnable bottles as well as the lack of a keg washer. The circularity* potential in Sharkia will be 61% as 9200 m^3/month of the 14961 m^3/month would be available for the orange orchard. Total N is for none of the processes limiting and based on Total N every brewery process effluent could be sent to the orange orchard.

How can the quality gap be closed between the water streams from the brewery and the desired water quality for the external user?

Based on the opportunities and bottlenecks found by the water pinch in the network design of the breweries and the orange orchard, solutions were addressed to increase the circularity of a brewery. The main bottlenecks were the high COD and Na^+ concentrations in some of the process effluents. Process effluents high in COD could be treated with anaerobic-aerobic treatment. As most breweries have a wastewater treatment plant with anaerobic-aerobic treatment this problem could be solved easily. To reduce the Na^+ load there are two possible solutions. One is to replace caustic with potassium hydroxide. Both breweries could become 100% circular on water when implementing an anaerobic-aerobic treatment facility and replace all $NaOH$ with KOH. The other solution for too high Na^+ concentrations, is to collect the caustic streams from the caustic baths separately. The water rinsing steps in the bottle washer, keg washer, crate washer and CIP installations could go to the orange orchard without treatment. The separate caustic stream could be reused multiple times and after some period be discharged to a WWTP. These caustic effluents could never be used by an orange orchard without treatment. This solution will increase the circularity potential of a brewery but will never achieve 100% circularity.

Can the water pinch method, as used for the case breweries, be applied to every brewery?

This research shows successfully that the water pinch can be used to determine to what extend the case breweries can be circular on water with an external user. Every potential external user could be used as long as data on limiting constituents is available. This also accounts for the choice of brewery. As long as data is available on water using processes, the water pinch can be used for every brewery. The higher the level of detailed data, the more specific conclusions and solutions could be found from the water pinch. The work shows that the water pinch is not only a water optimization tool but also a tool to measure the circularity potential. In the past, the water pinch was only used in the framework of a process plant, but this research shows that it can also be used for a multi-user network centred on a brewery. Besides, it shows the opportunities of circularity within the quality range that is already present, instead of changing the source water at all costs to meet the external user requirements. The method can be a start for many industrial sites including a brewery, in water scarce areas to identify the collaboration opportunities between the different users of the local watershed. This would contribute to achieve a circular economy.

6.2. Recommendations

In this section some recommendations for further research were given based on the conclusions drawn in this research.

This work is based on the single constituent water pinch method. The calculations were made by hand and for multi constituent and more complex networks, this method is far from perfect. Therefore, it is recommended to develop with the help of the results in this work a mixed integer non-linear program model. Example of MINLP could be found in work of Castro et al. (1999), Oliver et al. (2008), Nair et al. (2017) and Somoza-Tornos et al. (2019). All these researches used the water pinch as a base for a MINLP. The combination of the water pinch and a mathematical program would make it easy to generalise the analysing method developed in this work. Other optimization programs that could be used to upgrade the water pinch are fuzzy mathematical programs as described by Aviso et al. (2010).

Not only the extension of a mathematical model would help to optimize use of the water pinch but also the extension to analysis of more constituents is recommended. In this research only COD, Na^+ and Total N were considered but more constituents might be present and could restrict the reuse of process effluents of a brewery. To be able to give a well thought-out advice on the circularity opportunities of a brewery every possible constituent should be examined. Otherwise it cannot be guaranteed that the process effluent can be used without problems. This is especially important because trust is fragile and every possible threat that could harm the relation between users should be covered.

On the level of the breweries of Heineken it is highly recommended to gather more specific, process data. In this research quite some estimations were made and to implement this circularity network in practise exact values are necessary. When data is up to date, experts of the industries should examine the designed networks on their feasibility. The next step would be to check the economic benefits and drawbacks that are important factors to let the collaboration between different industries succeed.

The last recommendation is to apply the water pinch in combination with other material flows. The method described in this work could be used to optimize solid material flows of the brewery as well as heat. A combination of the heat pinch with water pinch with the focus on circularity would increase the circularity of a brewery as contributor of a circular economy.

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Appendix 1: UBM process water flowrate data

Table 23: UBM limiting data for key processes from El Obour brewery. Per key process, the UBM water flowrate is presented in m^3/month with corresponding concentration COD, Total N, Na^+ in mg/L. For processes with in red no UBM value was available and actual process water flowrate is used. Data based on Heineken measurements and information.

Key processes ***[No.]***		$f_{i,UBM}$ [m^3/month]	$COD_{lim, in}$ [mg/L]	$COD_{lim, out}$ [mg/L]	Total $N_{lim, in}$ [mg/L]	Total $N_{lim, out}$ [mg/L]	$Na^+_{lim, in}$ [mg/L]	$Na^+_{lim,out}$ [mg/L]
1	CO2 washer	596	0	0	4.00	4.00	0	0
2	Boilers	75	0	0	4.00	4.00	0	0
3	Cooling towers	1137	150	150	4.00	4.00	0	0
4	CIP brew house	709	0	103	4.00	4.38	11719	11719
5	CIP wort copper	213	0	1742	4.00	5.28	11719	11719
6	CIP wort cooler	993	0	73	4.00	4.27	11719	11719
7	BMF and PVPP air removal	142	0	0	4.00	4.00	0	0
8	CIP Cellars	1419	0	1573	4.00	4.65	11719	11719
9	Crate washer	93	250	1450	4.00	4.00	4073	4073
10	Bottle washer	748	200	1400	4.00	4.00	6453	6453
11	Bottle filler	187	30	201	4.00	4.46	0	0
12	Vacuum pump	853	200	200	4.00	4.00	0	0
13	Bottle pasteurizer	93	50	1391	4.00	4.01	0	0
14	Conveyor lubrication	256	100	241	4.00	4.53	0	0
15	Can filler	203	30	287	4.00	5.16	0	0
16	Can rinser	203	30	32	4.00	4.00	0	0
17	Can pasteurizer	81	50	692	4.00	5.06	0	0
18	Keg washer	463	0	1200	4.00	4.00	12508	12508

Table 24: UBM limiting data for key processes from Sharkia brewery. Per key process, the UBM water flowrate is presented in m^3/month with corresponding concentration COD, Total N, Na^+ in mg/L. For processes with in red no UBM value was available and actual process water flowrate is used. Data based on Heineken measurements and information.

Key processes [No.]		$f_{i,UBM}$ [m^3/month]	$COD_{lim,\ in}$ [mg/L]	$COD_{lim,\ out}$ [mg/L]	Total $N_{lim,\ in}$ [mg/L]	Total $N_{lim,\ out}$ [mg/L]	$Na^+_{lim,\ in}$ [mg/L]	$Na^+_{lim,out}$ [mg/L]
1	***Boilers***	1080	0	0	4.00	4.00	0	0
2	***Cooling towers***	2300	150	150	4.00	4.00	0	0
3	***CIP brewhouse***	1268	0	0	4.00	5.25	11719	11719
4	***CIP wort copper***	46	0	1403	4.00	5.98	11719	11719
5	***CIP wort cooler***	21	0	7	4.00	8.35	11719	11719
6	***CIP Cellars***	3803	0	1400	4.00	4.05	11719	11719
7	***Crate washer***	69	250	1450	4.00	4.00	38080	38080
8	***Bottle washer***	554	200	1400	4.00	4.00	2720	2720
9	***Filler + Vacuum***	138	0	1	4.00	4.44	0	0
10	***Vacuum pump***	852	200	200	4.00	4.00	0	0
11	***Bottle pasteurizer***	692	50	1350	4.00	4.00	0	0
12	***Conveyor lubricant***	430	100	100	4.00	4.00	0	0
13	***Can filler***	290	30	32	4.00	5.12	0	0
14	***Can rinser***	290	30	30	4.00	4.00	0	0
15	***Can pasteurizer***	869	50	50	4.00	4.00	0	0
16	***PET filler + rinser***	564	0	1	4.00	4.15	0	0
17	***PET pasteurizer***	1693	0	0	4.00	4.01	0	0

Appendix 2: Extract losses

Table 25: Extract losses per key process for El Obour brewery

Processes	Extract loss [%]
CO2 washer	0
Boilers	0
Cooling towers	0
CIP brew house	0.80
CIP wort copper	0.80
CIP wort cooler	0.80
BMF and PVPP air removal	2.70
CIP Cellars	2.70
Crate washer	0
Bottle washer	0
Filler + Vacuum	1.33
Vacuum pump	0
Bottle pasteurizer	0.16
Conveyor lubricant	1.50
Can filler	1.00
Can rinser	0
Can pasteurizer	1.00
Keg washer	0

Table 26: Extract losses per key process for Sharkia brewery

Processes	Extract loss [%]
Boilers	0
Cooling towers	0
CIP brew house	0.15
CIP wort copper	0.15
CIP wort cooler	0.15
CIP Cellars	0.47
Crate washer	0
Bottle washer	0
Filler + Vacuum	0.17
Vacuum pump	0
Bottle pasteurizer	0
Conveyor lubricant	0
Can filler	0.70
Can rinser	0.01
Can pasteurizer	0
PET filler + rinser	0.68
PET pasteurizer	0.01

Appendix 3: Initial water networks UBM and actual process water flowrates

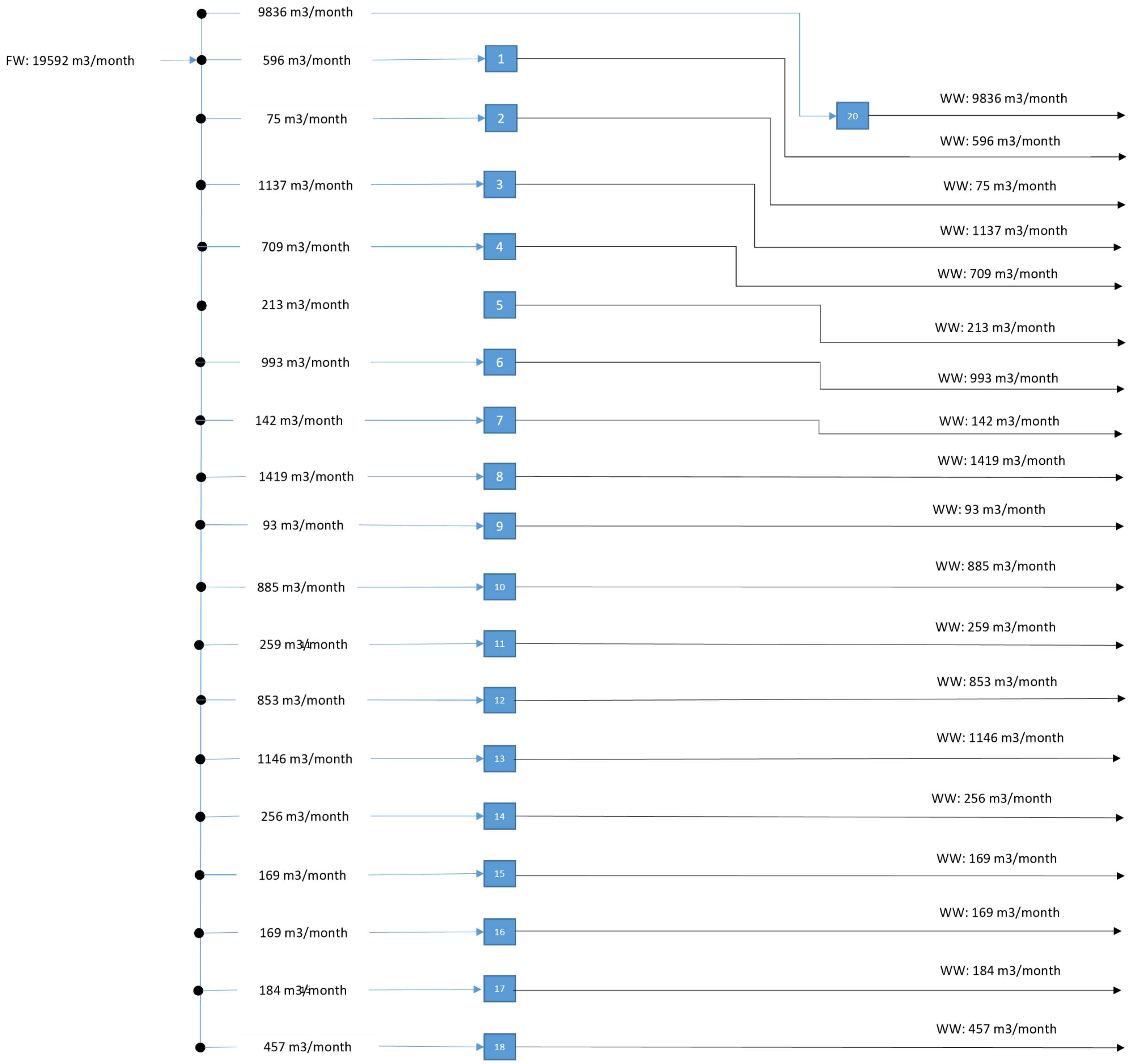

Figure 21: El Obour Initial water network based on actual process water flowrates. Blue arrows represents the influent stream, black arrows represents the effluent stream to the WWTP. Processes 1 till 18 correspond to brewery processes from Table 11.

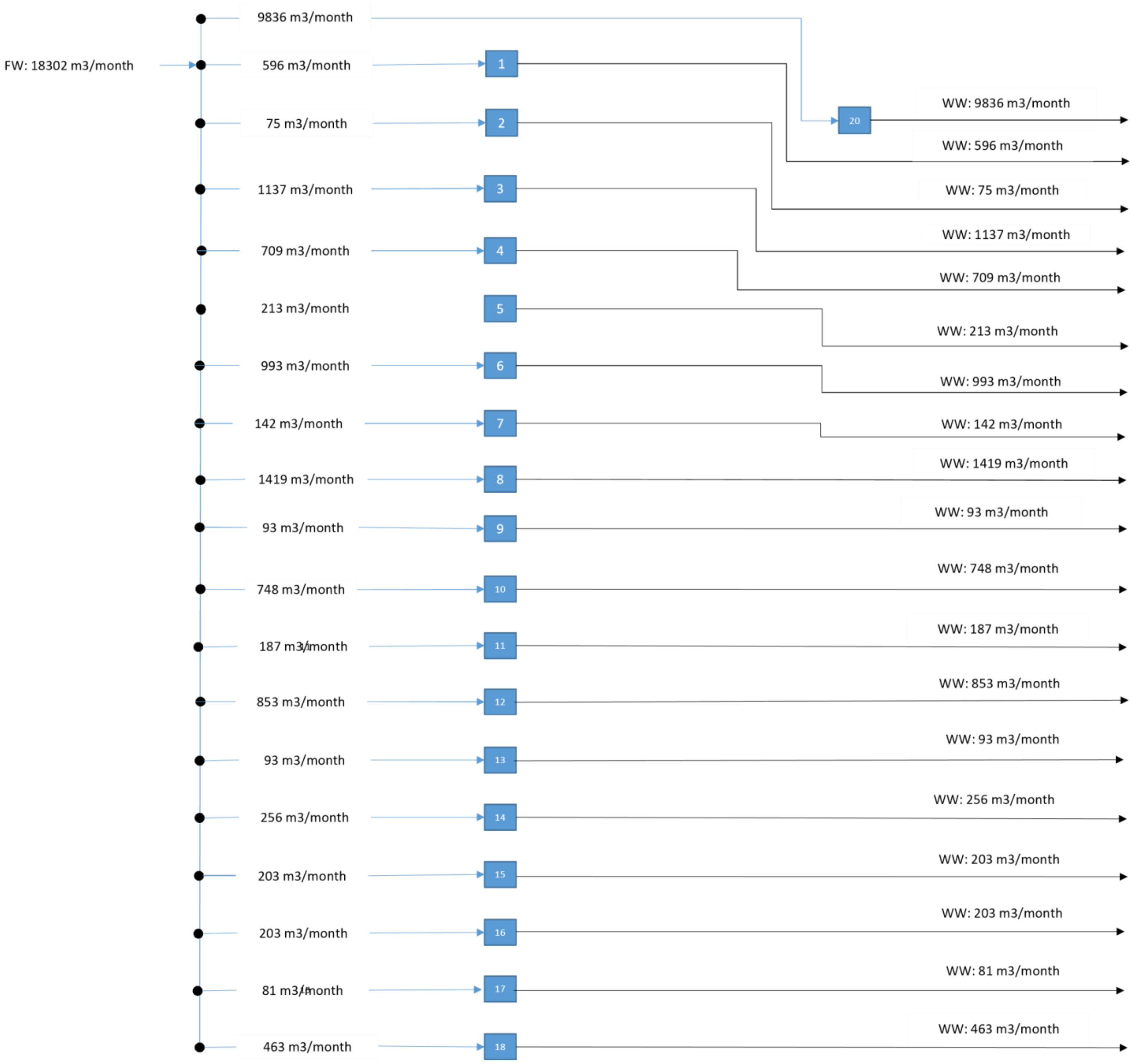

Figure 22: El Obour Initial water network based on UBM process water flowrates. Blue arrows represents the influent stream, black arrows represents the effluent stream to the WWTP. Processes 1 till 18 correspond to brewery processes from Table 11.

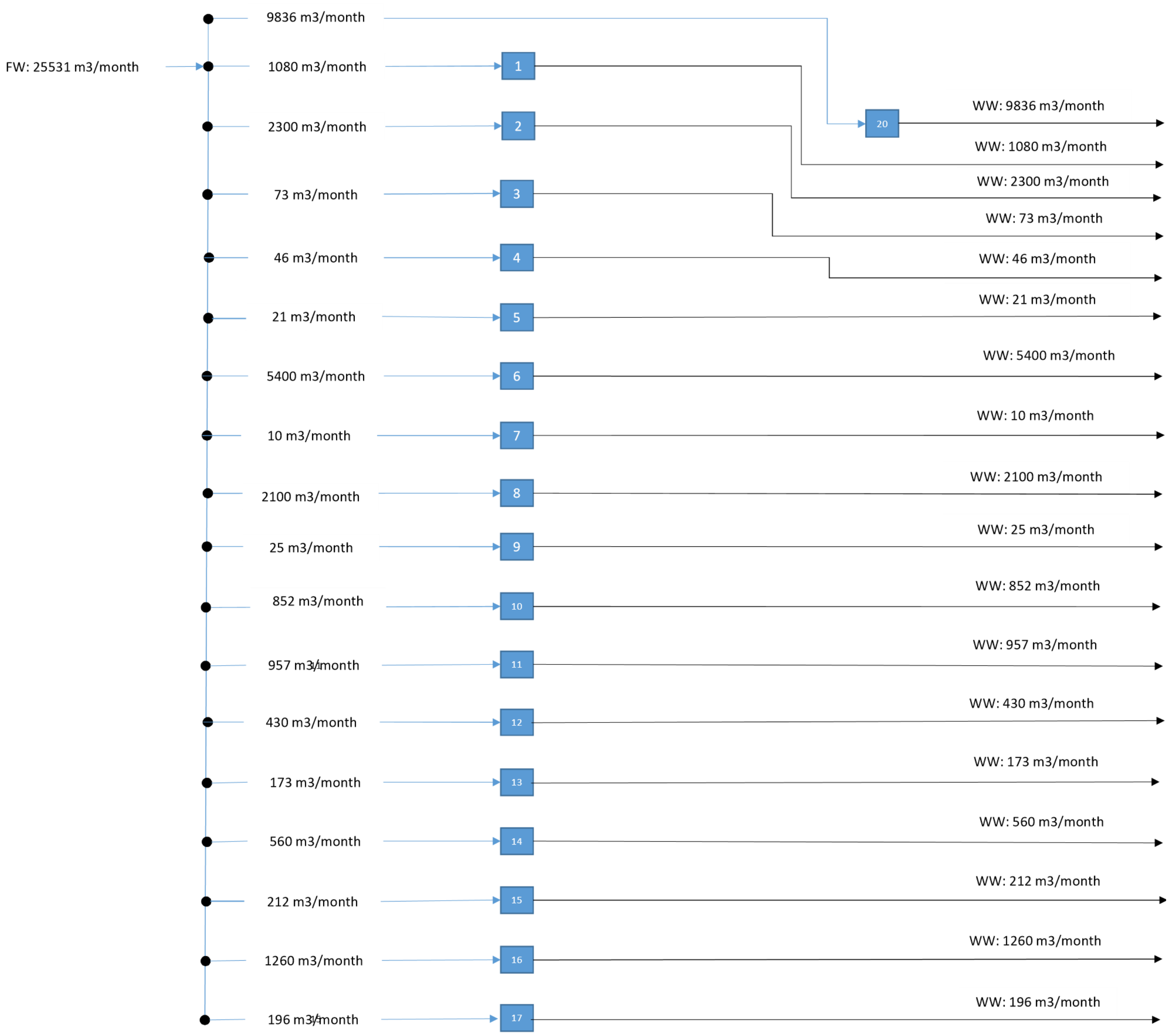

Figure 23: Sharkia initial water network based on actual process water flowrates. Blue arrows represents the influent stream, black arrows represents the effluent stream to the WWTP. Processes 1 till 17 correspond to brewery processes from Table 12.

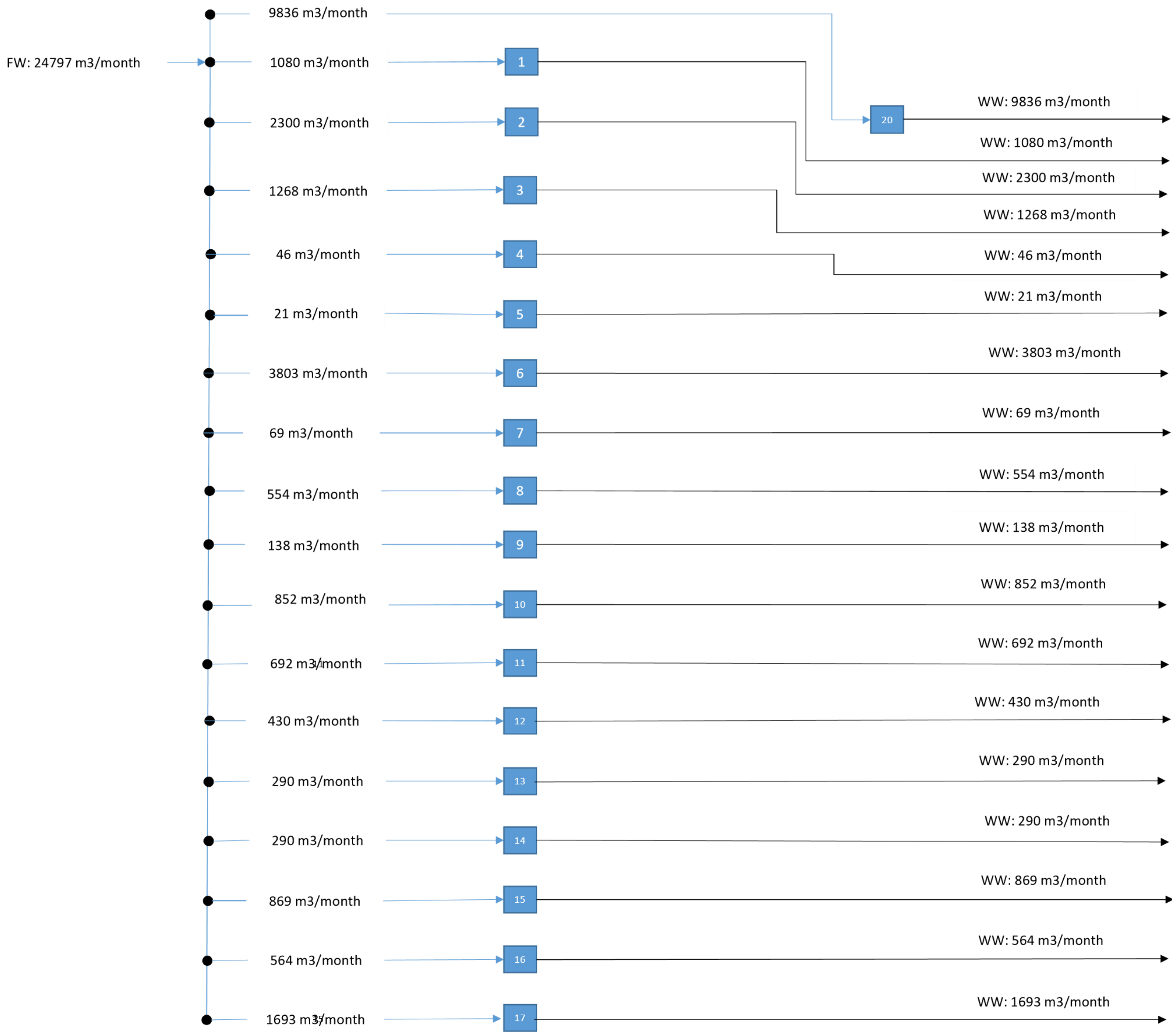

Figure 24: Sharkia initial water network based on UBM process water flowrates. Blue arrows represents the influent stream, black arrows represents the effluent stream to the WWTP. Processes 1 till 17 correspond to brewery processes from Table 12.

Appendix 4a: El Obour COD composite curve

Table 27: COD composite curve table with interval numbers and corresponding COD concentrations for El Obour brewery. For every interval the sum of the flowrates of the processes in that interval is shown, as well as the mass load and cumulative mass load. The last column represents the required fresh water flowrate in the network. The green highlighted cells are the pinch point characteristics. Calculations based on data from Table 11.

Interval [no.]	COD_j [mg/L]	$\sum f_j$ [m^3/month]	Δm_j [kg/month]	$\sum \Delta m_j$ [kg/month]	f_{ws} [m^3/month]
0	0	671	0	0	0
1	8	3933	31	31	3933
2	27	2230	42	74	2735
3	30	2088	6	80	2670
4	32	2686	5	85	2671
5	50	2517	45	131	2615
6	100	3846	192	323	3231
7	120	4102	82	405	3376
8	150	15076	452	857	5716
9	153	13938	44	901	5884
10	200	14532	681	1582	7911
11	241	14564	594	2176	9037
12	250	14308	132	2308	9232
13	335	14402	1218	3526	10539
14	339	14218	63	3589	10587
15	1200	14049	12096	15685	13071
16	1353	13593	2084	17770	13130
17	1400	12446	581	18351	13108
18	1408	11561	92	18443	13099
19	1427	11348	216	18659	13075
20	1450	9930	228	18887	13026
21	1500	9836	492	19379	12919

Appendix 4b: El Obour actual Na^+ network design

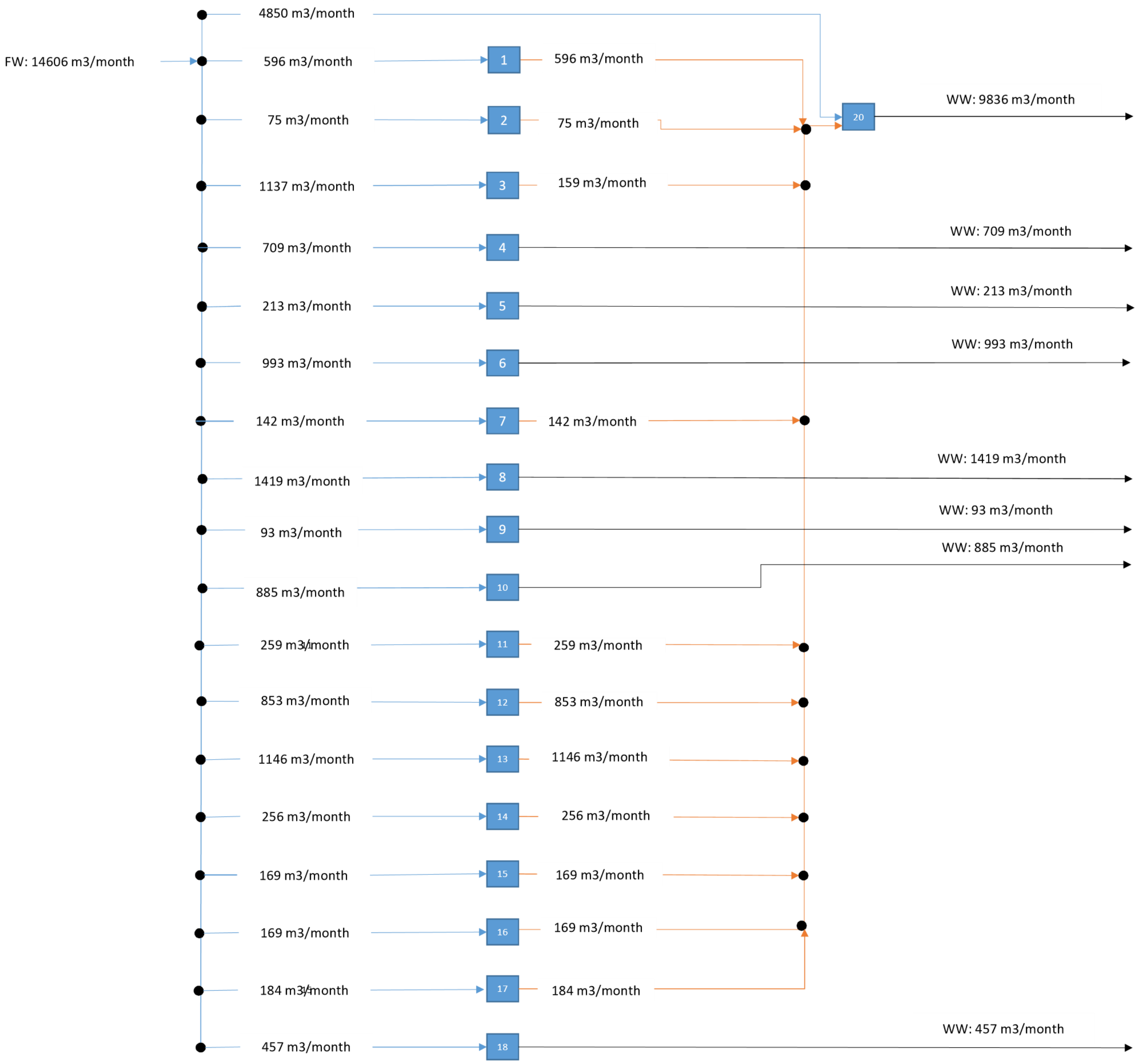

Figure 25: Na^+ limiting network design El Obour brewery and orange orchard. Process 1 till 18 refer to the process numbers in Table 11. Process 20 is the external user, in this case the orange orchard. Blue lines indicate fresh water inflow; orange lines indicate recirculation streams and black lines refer to wastewater sent to the WWTP.

Appendix 4c: El Obour Total N composite curve data

Table 28: Mass load table to construct Total N composite curve with key processes 1 till 18 and orange orchard 20. Per process the required water flowrate and maximum allowable Total N influent and effluent concentration are shown for El Obour brewery.

Process [No.]		$f_{i,actual}$ [m^3/month]	Total $N_{lim,in}$ [mg/L]	Total $N_{lim,out}$ [mg/L]	Δm_i [kg/month]
1	CO2 washer	596	4	4.00	0.00
2	Boilers	75	4	4.00	0.00
3	Cooling towers	1137	4	4.00	0.00
4	CIP brew house	709	4	4.38	0.27
5	CIP wort copper	213	4	5.28	0.27
6	CIP wort cooler	993	4	4.27	0.27
7	BMF and PVPP air removal	142	4	10.48	0.92
8	CIP Cellars	1419	4	4.65	0.92
9	Crate washer	93	4	4.00	0.00
10	Bottle washer	885	4	4.15	0.13
11	Bottle filler	259	4	4.46	0.12
12	Vacuum pump	853	4	4.00	0.00
13	Bottle pasteurizer	1146	4	4.01	0.01
14	Conveyor lubrication	256	4	4.53	0.13
15	Can filler	169	4	5.16	0.20
16	Can rinser	169	4	4.00	0.00
17	Can pasteurizer	184	4	5.06	0.20
18	Keg washer	457	4	4.18	0.08
20	Orange plant	9836	30	100	689

Table 29: Total N composite curve table with interval numbers and corresponding Total N concentrations for El Obour brewery. For every interval the sum of the flowrates of the processes in that interval are shown, as well as the mass load and cumulative mass load. The last column represents the required fresh water flowrate in the network. The green highlighted cells are the pinch point characteristics.

Interval [no.]	$Total\ N_j$ [mg/L]	$\sum f_j$ [m^3/month]	Δm_j [kg/month]	$\sum \Delta m_j$ [kg/month]	f_{ws} [m^3/month]
0	4.00	0	0	0	0
1	4.01	6832	0.09	0.09	6832
2	4.15	5686	0.79	0.88	5780
3	4.18	4800	0.15	1.02	5617
4	4.27	4344	0.40	1.42	5191
5	4.38	3351	0.37	1.79	4665
6	4.46	2641	0.20	1.99	4329
7	4.53	2382	0.16	2.15	4085
8	4.65	2126	0.26	2.41	3717
9	5.06	707	0.29	2.70	2541
10	5.16	524	0.05	2.75	2381
11	5.28	355	0.04	2.79	2184
12	10.48	142	0.74	3.53	545
13	30	0	0.00	3.53	136
14	100	9836	688.52	692.06	7209

Figure 26: Total N limiting network design El Obour brewery and orange orchard. Process 1 till 18 refer to the process numbers in Table 11. Process 20 is the external user, in this case the orange orchard. Blue lines indicate fresh water inflow; orange lines indicate recirculation streams and black lines refer to wastewater sent to the WWTP.

Appendix 4d: Integrated network El Obour - UBM

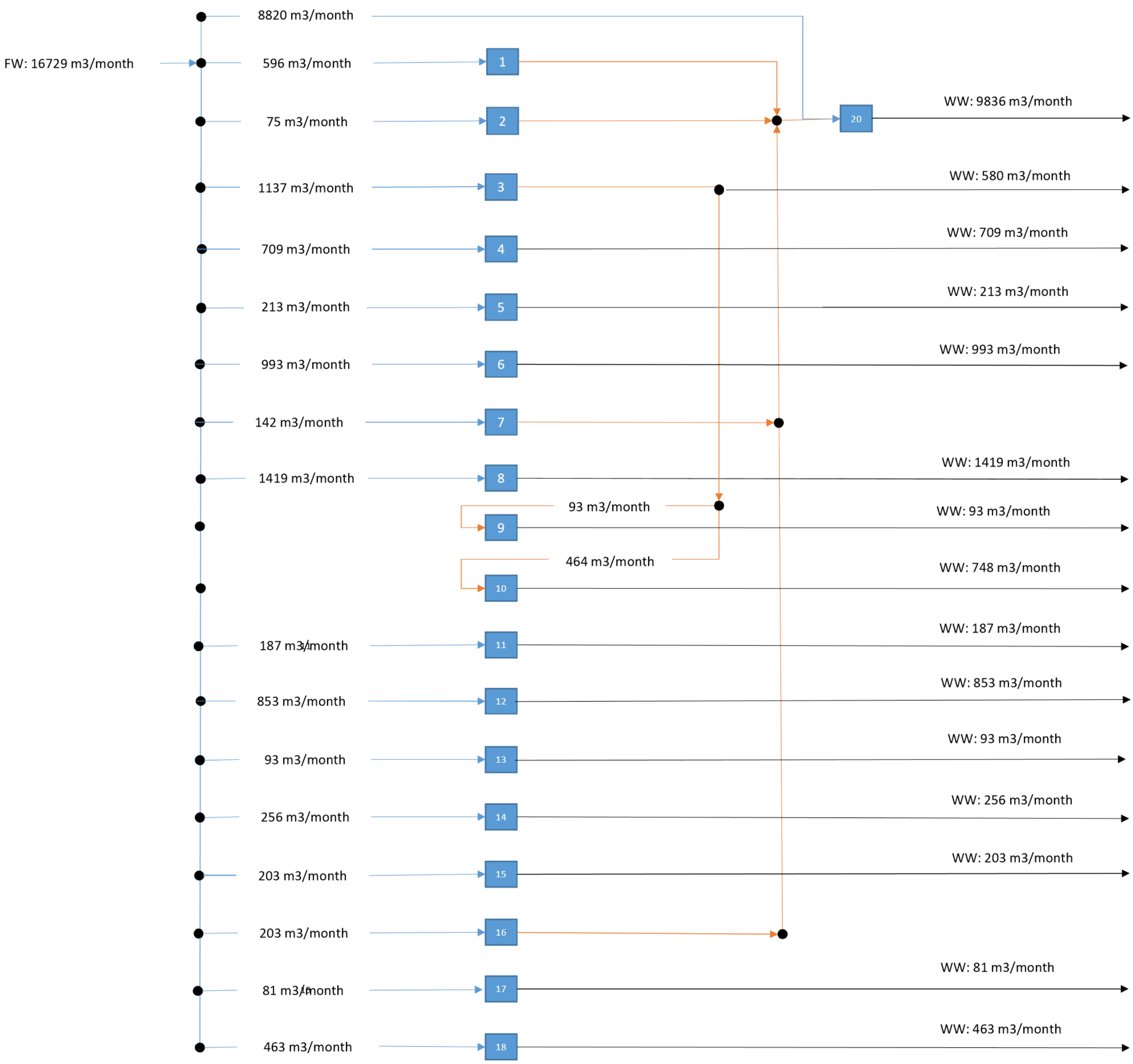

Figure 27: UBM integrated network design for El Obour brewery. Process 1 till 18 refer to the process numbers in Table 11. Process 20 is the external user, in this case the orange orchard. Blue lines indicate fresh water inflow; orange lines indicate recirculation streams and black lines refer to wastewater sent to the WWTP.

Appendix 5: Integrated networks Sharkia

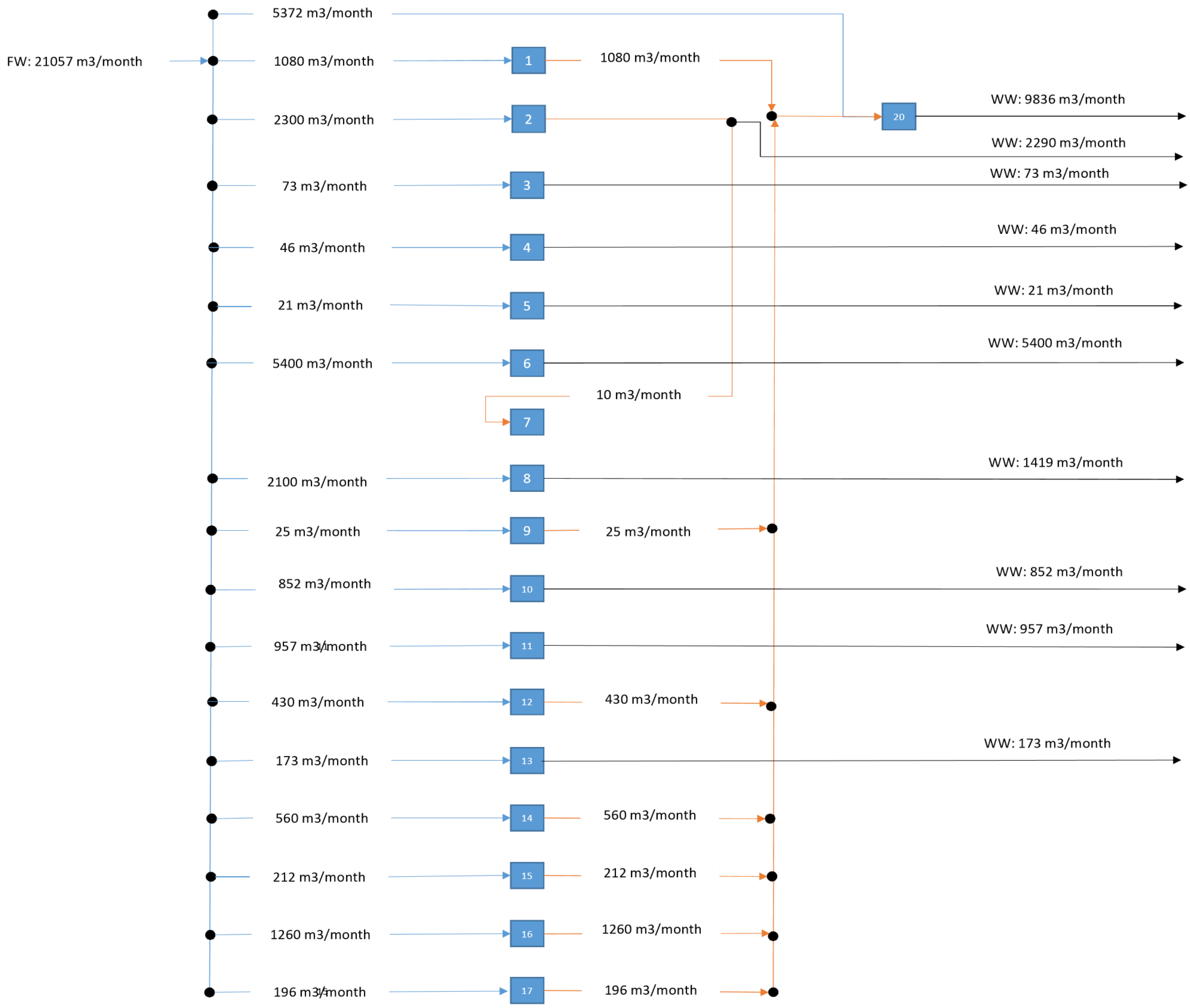

Figure 28: UBM integrated network for Sharkia with orange orchard as external user complying to key constituents COD, Na+ and Total N. The brewery of Sharkia is 34% circular on water. Process 1 till 17 refer to the process numbers in Table 12. Process 20 is the external user, in this case the orange orchard. Blue lines indicate fresh water inflow; orange lines indicate recirculation streams and black lines refer to wastewater sent to the WWTP.

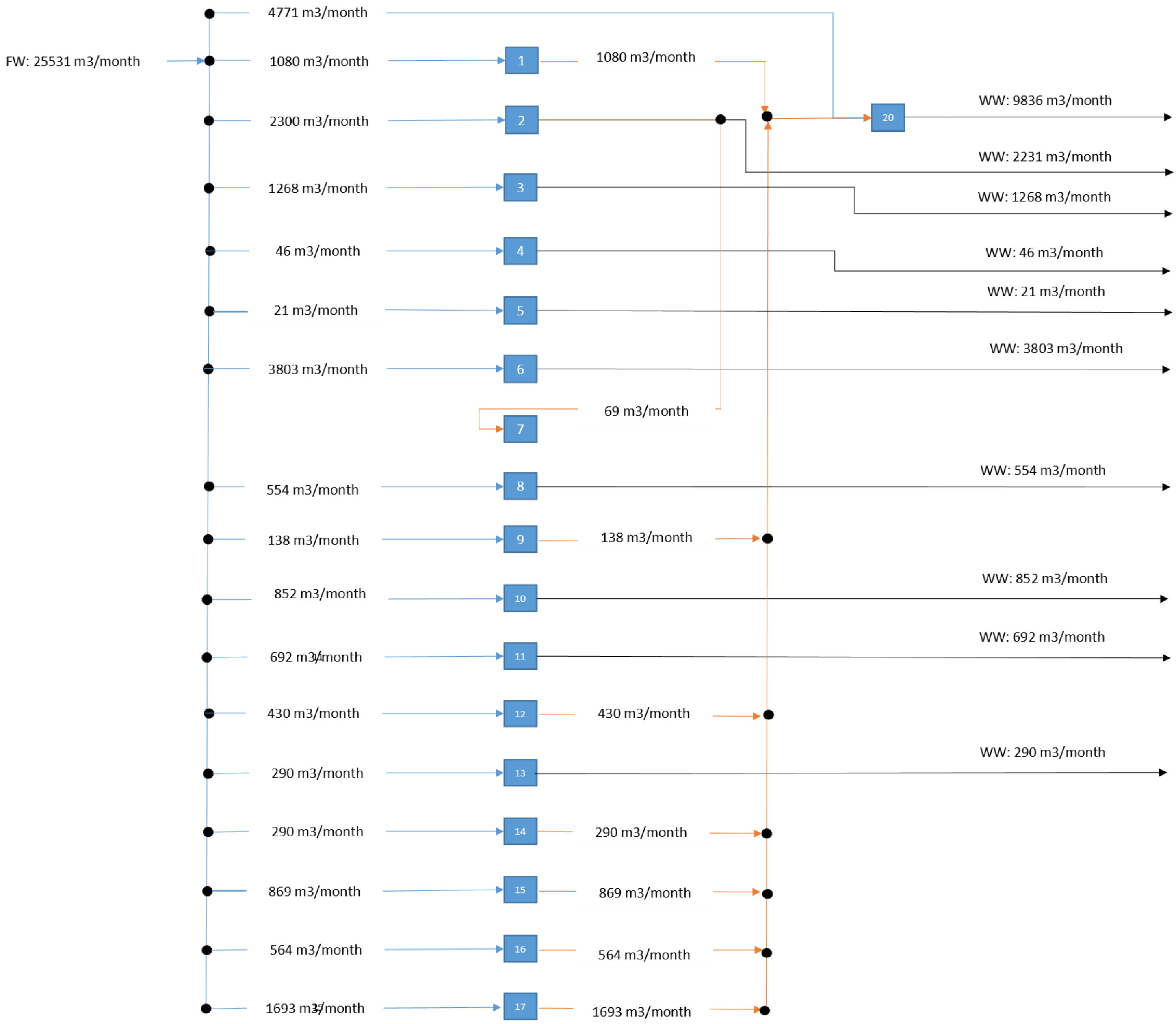

Figure 29: Actual integrated network for Sharkia with orange orchard as external user complying with the key constituents COD, Na+ and Total N. Process 1 till 17 refer to the process numbers in Table 12. Process 20 is the external user, in this case the orange orchard. Blue lines indicate fresh water inflow; orange lines indicate recirculation streams and black lines refer to wastewater sent to the WWTP.