THE USE OF WATER PINCH ANALYSIS TO DETERMINE OPTIMUM EFFLUENT TREATMENT CONDITIONS FOR AN INTEGRATED PULP AND PAPER MILL

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Abstract

Pulp and paper mills are facing the possibility of stricter effluent discharge limits. End-of-pipe treatment for discharge no longer guarantees compliance, nor is it the most cost-effective way of solving mills' effluent problems. In this dissertation, water pinch analysis is used as a tool to determine the optimum effluent treatment conditions to ensure compliance at the least cost to the mill. It is also shown that the environment and the mill can benefit simultaneously if the correct effluent discharge philosophy is implemented.

Mill simulation results were used to set up a water pinch analysis model. Maximum permissible inlet concentrations were specified for all process units. Mass transfer equations were used to describe the relationships between inlet and outlet concentrations of the process units. A number of generic effluent treatment units with preset performance specifications were added to the pinch model. These treatment units can be sized and used in an optimal way by the pinch model to obtain an optimum effluent treatment and recycling scheme. Capital and operating costs for different treatment units were included in the analysis. The capital cost for treatment units decrease as the volume treated by the unit decreases. The operating cost is generally expressed in terms of volume; however, certain treatment units have treatment cost expressed on load treated rather than volume.

The validity of the results obtained from *WaterPinch*™, the pinch analysis software used for building the pinch model, was checked by using a process simulation package, *WinGEMS*™, to simulate the proposed effluent treatment scenarios. This step ensured that the mass transfer relationships used in the water pinch model were valid. This was an important part of the work, as the results generated by the optimisation model have to be reliable in order to make the results obtained applicable to the mill.

The verified water pinch model was used to find optimum treatment plant layouts for different effluent discharge volume and concentration specifications. This resulted in an optimum-cost profile for a range of effluent discharge volumes and concentrations.

Optimum-cost profiles could be a decision making tool in the negotiation between the mill and the regulatory authority to set effluent discharge regulations in such a way that the environment benefits without unnecessarily restricting economical and social development of the region.

Using optimum-cost profiles, the differences between a load-based and a concentration-based discharge permit was illustrated. Comparing the pinch analysis results for these scenarios showed that the mill has no financial incentive to reduce effluent volume if a concentration-based permit is in place. However, a load-based permit could make it financially viable for a mill to reduce effluent volume and load rather than to simply treat and discharge. It is also shown that both the mill and the environment (river) benefit from a load based permit.

The impact of possible future waste discharge charges on the economical feasibility of various effluent treatment options is also investigated. The results indicate that the implementation of waste discharge charges will only benefit the environment if it is linked with a load-based effluent discharge permit. This illustrates the usefulness of pinch analysis as a basic risk analysis and risk management tool.

Preface

I, Maryna Mansfield, declare that unless indicated, this dissertation is my own work and that it has not been submitted, in whole or part, for a degree at another University or Institution.

The opinions expressed in this dissertation are that of the author, and not necessarily that of Sappi.

....
Maryna Mansfield
December 2005

As Maryna Mansfield's supervisor I have approved this dissertation for submission

....
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Abbreviations

BAT	Best Available Techniques
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
DAF	Dissolved Air Flotation
DO	Dissolved Oxygen
DWS	Dissolved Wood Solids
ECF	Elemental Chlorine Free
EDR	Electrodialysis Reversal
G/L	Green Liquor
GAMS	General Algebraic Modeling System
HBL	Heavy Black Liquor
HEN	Heat Exchanger Networks
HRL	Heavy Red Liquor
LP	Linear Programming
MEN	Mass Exchanger Networks
MILP	Mixed Integer Linear Programming
MIM	Minimum Impact Mill
MINLP	Mixed Integer Non-Linear Programming
MSA	Mass Separating Agents
MVR	Mechanical Vapour Recompression
NLP	Non-Linear Programming
NSSC	Neutral Sulphite Semi-Chemical Pulping
OCC	Old Corrugated Containers
ODtpd	Oven-dried tons per day
RO	Reverse Osmosis
SRF	Soda Recovery Furnace or Recovery Boiler
SRL	Strong Red Liquor
SS	Suspended Solids without Ash
SWL	Strong White Liquor
TA	Total Alkali
TCF	Totally Chlorine Free
TDS	Total Dissolved Solids
TMP	Thermo Mechanical Pulp
tpd	Tons per day

TSS	Total Suspended Solids
WBL	Weak Black Liquor
WRL	Weak Red Liquor
WWL	Weak White Liquor
ZLE	Zero Liquid Effluent

Glossary

Black liquor	Mixture of cooking chemicals and dissolved wood material remaining after sulphate cooking; recovered during pulp washing. concentrated by evaporation and burned in the recovery boiler to regenerate the cooking chemicals and generate energy.
Copeland reactor	A special type of **Recovery boiler**
Dissolved Wood Solids	The portion of the wood that is dissolved during the cooking process. Dissolved wood solids are organic and adds COD to effluent streams. Most of the dissolved wood solids generated during cooking are washed out of the pulp and burnt in a recovery boiler to recover energy and inorganic cooking chemicals.
Elemental Chlorine Free	ECF papers are made exclusively with pulp that uses chlorine dioxide rather than elemental chlorine gas as a bleaching agent. This virtually eliminates the discharge of detectable dioxins in the effluent of pulp manufacturing facilities.
Fluting	Paperboard used to make the corrugated layer in corrugated board.
Green liquor	The intermediate chemicals generated in the kraft recovery system. This liquor contains the regenerated sodium sulphide.
Heavy Black Liquor	See **Spent Liquor**
Heavy Red Liquor	See **Spent Liquor**
Integrated mill	A pulp and paper mill which is self-contained as regards its fibre; i.e. a pulp mill which produces pulp exclusively for the on-site paper mill, and/or a paper mill which sources all its fibre from the on-site pulp mill.
Kraft pulping	The Kraft process is the world's predominant chemical pulping process. The name is derived from the German word for "strong". The method involves cooking (digesting) wood chips in an alkaline solution for several hours during which time the chemicals attack the lignin in the wood. The dissolved lignin is later removed leaving behind the cellulose fibres. Unbleached kraft pulp is dark brown in colour, so before it can be used in many papermaking applications it must undergo a series of bleaching processes.

Lignin	A non cellulose material found in vegetable plants that may be considered as a binding agent or cement between the fibres of the plant.
Liner	Packaging board used as a surface layer on corrugated board or strong cartonboards.
NSSC pulping	This pulping process utilises sodium sulphite cooking liquor which is buffered with sodium carbonate to neutralise the organic acids liberated from wood during cooking.
Old Corrugated Containers	An important grade of recovered paper for making recycled corrugated cases.
Oxygen Delignification	A process in which oxygen gas and sodium hydroxide are used to remove lignin from brown stock.
Recovery Boiler	Boiler used to burn black liquor from chemical pulping for recovery of inorganic chemicals as well as for energy production.
Recovery system	System in a pulp mill where black liquor is burned and inorganic chemicals are recovered and circulated in the process.
Sack paper	Kraft paper, usually un-calendered, used to make paper sacks; also called sack kraft.
Spent liquor	Waste liquids from pulping and washing. Kraft pulping produces black liquor and NSSC pulping produces red liquor. See **Black Liquor.**
Strong Red Liquor	See **Spent Liquor**
Sulphite pulp	A papermaking fibre produced by an acid chemical process in which the cooking liquor contains an excess of SO_2. The sulphite liquor is a combination of a soluble (such as ammonium, calcium, sodium, or magnesium) and sulphurous acid.
Thermo mechanical pulp	A mechanical pulping process in which woodchips are softened by steam before passing through a mechanical refiner. Softening the pulp before refining reduces the damage to individual fibres, but the energy requirement is much higher than with the groundwood or refiner process.

Total Alkali $NaOH + Na_2S + Na_2CO_3 + 0.5*Na_2SO_3$ all expressed as Na_2O in alkaline pulping liquor.

Totally Chlorine Free Totally chlorine free applies to virgin fibre papers that are unbleached or processed with a sequence that includes no chlorine or chlorine derivatives.

White liquor The cooking chemicals applied to the digester - sodium hydroxide and sodium sulphide.

Whitewater All waters of a paper mill which have been separated from the stock or pulp suspension, either on the paper machine or accessory equipment such as thickeners, washers and save-alls, and also from pulp grinders. It carries a certain amount of fibre and may contain varying amounts of fillers, dyes, etc.

Outline of thesis

Chapter 1 gives a background of the impacts of Sappi Tugela mill on the Tugela River, and sets out the reasons for and the objectives of the study.

Chapter 2 gives a brief overview of mill operations, water usage and effluent discharge.

In *Chapter 3*, a literature review is presented on effluent recycling and re-use in the pulp and paper industry. The alternatives considered are cleaner production, internal recycling and treatment and recycling. The benefits and drawbacks of *system closure* are also investigated. A need is also expressed for the development of tools, such as process integration that link economics and environmental impact, which will present industry's technical constraints to regulators in a transparent and verifiable way, to help establish effective environmental regulations that will not deter innovation.

Chapter 4 contains a literature review on process integration. This includes graphical pinch analysis techniques as well as numerical approaches. The application of pinch analysis in the pulp and paper industry is also reviewed.

The methodology that was followed in setting up a water pinch optimisation model for Tugela mill is outlined in *Chapter 5*. This includes mass transfer relationships, concentration constraints, flow limits, cost data and treatment unit specifications.

The first step in water pinch analysis is obtaining a mass balance of the system, in this case the entire mill. This mass balance was set up by the author in a prior exercise for Sappi, using the *WinGEMS*™ simulation package. The simulation report and results for the *WinGEMS*™ mass balance is contained in *Appendix A*.

Chapter 6 contains the results of the water pinch analysis, including verification of the results obtained with the water pinch model against the *WinGEMS*™ simulation. The effect of a load based versus concentration based discharge limit is extensively examined through the use of optimum-cost profiles, developed with the water pinch model. The effects of possible effluent discharge tariffs and other factors on the resulting water pinch solution are also considered.

Chapter 7 contains a discussion on the results obtained in *Chapter 6*. *Chapter 8* lists the conclusions and recommendations of the study. The main conclusion is that water pinch is a useful tool that can be used by industry and government to find effluent discharge solutions that are beneficial to the environment whilst minimising cost to industry.

Chapter 1 Introduction

Sappi Tugela Mill and other mills are facing stricter effluent discharge regulations, and could in future be forced to employ additional effluent treatment technologies to ensure compliance. There are several treatment options available, from simple effluent treatment and discharge options to more complex treatment and recycling options. A further factor that may impact on the treatment network design employed is the impending effluent discharge tariffs that mills will have to pay for discharging effluent to the river.

1.1 Background

SAPPI Tugela Mill is located in the Tugela River Catchment, at the downstream end of the catchment, approximately 15km from the Tugela River mouth. The Tugela River drains one of the major catchments (28920 km^2) in the country and is fed by several rivers including the Buffalo, Sundays, Mooi and Bushmans Rivers. The Tugela River water resources are utilised for a variety of uses, including transfers to the Vaal River and specifically Gauteng as well as transfer to Richards Bay on the KwaZulu-Natal North Coast. Local water abstraction and inter-basin transfers of water at times result in low flow conditions at the mouth of the Tugela River.

The natural river flow is seasonal and this is further influenced by upstream impoundments. During drought conditions, the river flow has at times dropped to less than 1.0 m^3/sec at Mandini. This is very low, if it is taken into account that the Tugela Mill requires on average 0.5 to 0.7m^3/sec before having to curtail production. The historical low flow conditions are characterised by the following statistics:

- 1 percentile flow = 1.03m^3/sec
- 5 percentile flow = 2.28m^3/sec

1.1.1 Effluent Discharge Impact Assessment

Tugela Mill conducted an impact assessment of their effluent discharge to the Tugela River in 1997/98. The impact assessment developed a perspective on the following water-related aspects:

- Spectrum of water users located downstream of the Mill
- Water user requirements downstream of the Mill
- Probable impact associated with the future treated effluent (waste) discharges on the downstream water users

The main findings of the assessment are detailed below.

1.1.1.1 Water Users

The recognised water users located downstream of the Mill effluent (waste) discharge include:

- *Aquatic ecosystems* - The Tugela is a river of national importance and a healthy aquatic ecosystem is a minimum requirement in terms of the new National Water Act, Act 36 of 1998.
- *Potable Water Supply* - The potential exists for the abstraction of water directly from the river for small scale and informal potable water use.
- *Irrigation* - Water is abstracted for irrigation of sugar cane, citrus and bananas. The citrus trees are considered to be relatively sensitive to poor quality irrigation water.
- *Recreation* - Water-related recreation is mainly related to tourism and fishing at the river mouth. Water contact recreation is minimal.

1.1.1.2 Water Quality Requirements

A review of the water quality requirements by users and the probable river water quality downstream of the Mill effluent discharge point, revealed a number of water quality variables of concern:

- *Aquatic ecosystems*

  Aquatic life is sensitive to low Dissolved Oxygen (DO) levels and the target is to keep the DO levels above 80 % of saturation.

  High salinity. as reflected by TDS, may also impact aquatic life, but biota can adapt over a period of time if the salinity is consistently higher than the background.

- *Potable Water Supply*

  The main requirements with respect to potable water use are protection of health, aesthetically acceptable appearance and acceptable cost of treatment. Salinity, with the main constituents in this case being sodium and sulphate, may impart a salty taste at high salinity levels. Elevated sulphate may cause diarrhoea in sensitive individuals. The water must also not be coloured to be aesthetically acceptable.

- *Irrigation*

  The main requirements of acceptable irrigation water are protection of salt-sensitive crops, maintenance of high crop yields, protection of soil and protection of irrigation equipment.

Salinity, specifically the sodium concentration levels, is the primary concern. High salinity may result in crop yield reduction, high sodium could result in foliar damage if applied to leaves and could also damage the soil structure over time.

- *Recreation*

  The non-contact recreational use of the water requires an absence of unnatural colour and objectionable odours.

1.1.1.3 Impacts Associated with Effluent Discharges

The probable impacts associated with the Mill effluent discharge are outlined for each of the water quality variables of concern.

- *Dissolved Oxygen*

  The DO levels will be below the target level for healthy aquatic life, but will be above the minimum acceptable levels for most of the time. The Tugela River DO levels upstream of the Mill effluent (waste) discharge point, are already below the target DO concentration, but the situation improves progressively further downstream.

  The maintenance of acceptable DO levels in the river is the primary water quality issue from the perspective of maintaining a healthy aquatic ecosystem in the river.

- *Salinity (TDS)*

  The salinity impact is in a range where minimal reduction in crop yield (less than 5 % reduction) can be expected. Water may start having a salty taste, if the river flow drops below $2m^3$/sec, but no health effects are likely.

  The salinity will exceed the target variation of less than 15 % above the background level, only when the river flow drops below $4m^3$/sec.

- *Sodium*

  Sodium levels will exceed the target for irrigation when the river flow drops below $4m^3$ /sec. Below this river flow, citrus trees may experience foliar damage if using a sprinkler irrigation system.

  The water may also have a salty taste due to the presence of sodium when the river flow drops below $2m^3$/sec. and some health-related effects may be felt by sensitive individuals.

- *Sulphate*

  Sulphate in potable water will only become a concern at very low river flows, less than $1m^3$/sec.

- *Colour*

  The colour levels in the river will substantially exceed the potable water target levels. Very limited. if any, direct abstraction of river water for potable use is however taking place.

In summary, the main water quality variables of concern include:

- Acceptable DO levels must be maintained to support a healthy ecosystem
- Salinity and specifically sodium will have to be managed.
- Colour only impacts a small potential user, but may have to be addressed in the longer term.

This dissertation will not attempt to prove or disprove the need for further effluent treatment at Tugela mill. It is assumed that some form of effluent treatment is or will be required, but that the exact treatment requirements are not clear.

1.2 Objective of the investigation

In the light of the above, Sappi Tugela Mill could face stricter effluent discharge regulations that would force the mill to employ additional effluent treatment technologies to ensure compliance.

Setting a suitable discharge limit that would benefit the river and all its users without unnecessary risk and cost to the mill may not be an easy task, considering the various social, economical and political factors involved. This process could be simplified if a tool can be found that explains the cost and risk to the mill for various effluent discharge limits. This tool must be able to objectively find the lowest cost of treatment for each possible discharge limit, so that the results can be evaluated and used to make informed decisions regarding best discharge structure.

The aim of this dissertation is to propose *water pinch analysis* as the tool for helping government, but also the mill to find the best solution. Although water pinch analysis does not purport to assess all the impacts on the river, it does quantify the cost impact of a given discharge limit on the mill. It can also predict how the mill would react to a given discharge limit, in other words whether a certain discharge regulation would encourage the mill to reduce effluent as much as possible, or not.

From the mill's perspective. there are several treatment options available, from simple effluent treatment and discharge options to more complex treatment and recycling options. A further factor that may impact on the treatment network design employed is the impending effluent discharge tariffs that mills will have to pay for discharging effluent to the river. Water pinch analysis can be used by the mill to design a system to comply with regulations at the lowest possible cost.

The use of *optimum-cost profiles*, developed using water pinch analysis, will be evaluated for its potential as a transparent tool for regulator and industry to find solutions that will benefit the environment without the industry being penalised unnecessarily.

In order to prove useful, the developed technique has to show that the ultimate solution is beneficial to both the mill and the river.

This will be done by:

- comparing the optimised costs for a load based and concentration based discharge limit.
- comparing contaminant load discharged to the river for load based and concentration based discharge limit.
- comparing the cost of all pinch analysis solutions to the cost of conventional (un-optimised) treatment technologies.

The usefulness of pinch analysis to do basic risk analysis will also be demonstrated by using water pinch analysis to examine the effects of possible effluent discharge tariffs and cost variations on the ultimate treatment solution.

The validity of the results obtained through the pinch analysis will be tested and verified using an existing mill simulation.

Chapter 2 Mill Overview

2.1 Background

Tugela mill is an integrated pulp and paper mill that produces various unbleached paper grades, including sack-kraft, fluting and liner.

The mill employs Kraft (softwood) and Neutral Sulphite Semi-Chemical (NSSC) pulping (hardwood) for pulp production. Waste fibre is also used as an additional fibre source.

Figure 2-1 shows a schematic layout of the mill operations.

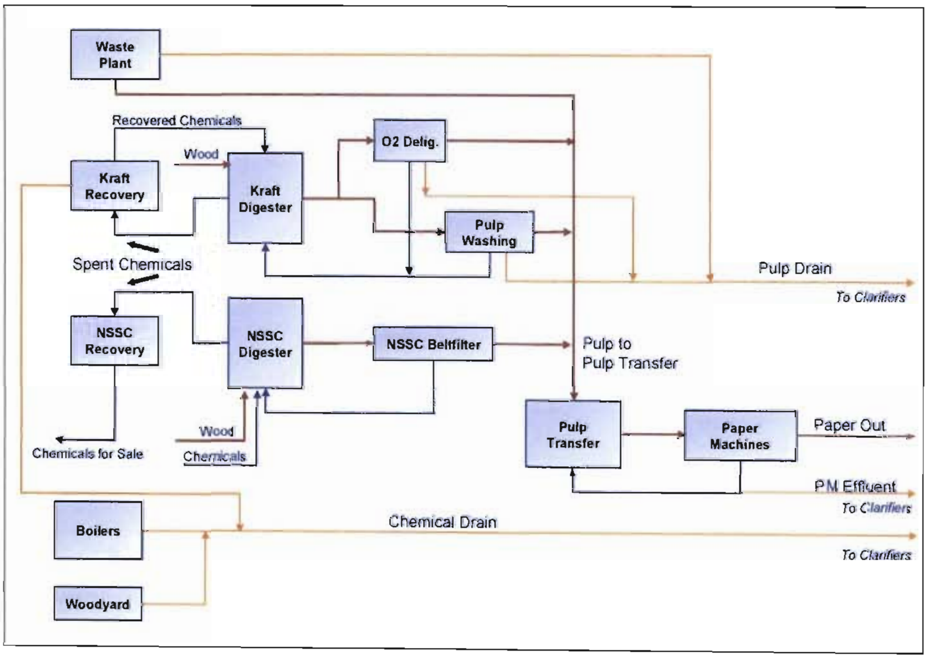


Figure 2-1 Mill operations

Process water is abstracted from the Tugela River and all effluent is discharged back to the river. Currently, the mill water and effluent system is very open, with effluent totalling 50Ml/day (2080m^3/h), or 50m^3/ton paper produced.

2.2 Mill operations overview

2.2.1 Kraft pulping and recovery

Pine woodchips from the woodyard is pulped in a Kraft continuous digester under high heat and pressure. The pulp yield from wood of this process is approximately 48% on wood. The main pulping chemical used is caustic soda, fed to the digester in the form of strong white liquor (SWL).

At the bottom of the digester, the cooked pulp is separated from the spent liquor. From here, a portion of the pulp is washed, and the rest is sent through an oxygen delignification step. In this step, more lignin is removed from the pulp through the addition of oxygen at alkaline conditions. This step results in a further pulp yield loss, and therefore also COD generation.

The pulp from both lines is washed using evaporator condensate. All washing is counter-current, with the wash water being recycled back into the digester. Liquor is then extracted from the digester as Weak Black Liquor (WBL).

The spent WBL is taken to the recovery section, where it is concentrated in evaporators and burnt in a soda recovery furnace, to produce sodium carbonate smelt. The smelt is then dissolved, producing green liquor, and re-causticised using lime. This produces strong white liquor and lime mud, $CaCO_3$. After separation in the strong white liquor clarifier, the SWL is fed to the digester, and the lime mud is fed to the lime kiln, where it is converted back to lime.

As soda losses occur through the pulp leaving the digester, it is necessary to make up the losses into the circuit. This is done by taking some of the red liquor from the NSSC recovery circuit into the Kraft circuit, thus making up soda and sulphidity losses.

2.2.2 NSSC pulping and recovery

Gum woodchips from the woodyard are pulped in an NSSC continuous digester under high heat and pressure. The pulp yield from wood of this process is approximately 75% on wood. The reason for the higher yield is because the NSSC is a semi-chemical process. The pulping chemicals used are sodium sulphite, buffered in a caustic solution.

At the bottom of the digester, the cooked pulp is separated from the spent liquor, and further refined before being washed, partially dewatered and stored for use in the paper machines.

The spent weak red liquor (WRL) is taken to the recovery section, where it is concentrated in evaporators and burnt in a fluidised bed reactor, to produce sodium sulphate product, which is sold commercially.

A portion of the weak red liquor is used to make up the soda losses in the Kraft recovery circuit.

2.2.3 Pulp transfer

The pulp produced in the pulp plants is partially de-watered and stored, from where it is re-diluted using paper machine backwater and transferred to the four paper machines.

2.2.4 Waste Plant

In the waste plant, recycled waste paper is pulped and screened to produce waste fibre. This fibre is used as part of the fibre source in certain paper grades produced by the mill.

2.2.5 Paper machines

There are four paper machines in the mill, producing various grades of paper. Each paper grade uses a different mix of Kraft. Oxygen Delignified, NSSC, waste and broke fibre. The paper machines use a large amount of water to dilute the pulp for cleaning and screening. This water is removed in the wire and press sections. from where a portion of it is cleaned and re-used, but the larger portion overflows to effluent. The effluent contains a large amount of fibre. Due to the large amounts of water passing through the paper machines, it follows that most of the recycling opportunities will be in the paper machine area.

2.2.6 Water usage

The mill abstracts approximately 55Ml/day (2290m^3/h) river water from the Tugela River. Of this amount, approximately 15 Ml/day (625m^3/h) is taken to a filtration plant, where the water is treated to domestic water standards.

Mill water is used in most applications in the mill, except for areas where higher quality domestic water is required. The largest domestic water users in the mill are the boilers, which use demineralised domestic water for boiler feed water make-up.

Of the 55 Ml/day (2290m^3/h), 5 Ml/day (208m^3/h) is evaporated in various mill operations. The largest of these are the evaporation in the recovery furnaces and the evaporation in the paper machine drying sections. The water usage split throughout the mill is shown in Table 2-1.

Table 2-1 Total mill water and domestic water usage per plant

Plant	Total Water Usage (m^3/h)	Percentage of Total Water Usage
Paper Machines 1,2 & 3	1008	43.4
Boilers	448	19.3
Paper Machine 4	263	11.3
Recovery	211	9.1
NSSC Pulping	183	7.9
Kraft Pulping	101	4.4
Waste Plant & Pulp Transfer	92	4.0
Woodyard	14	0.6
Total	**2320**	

2.2.7 Effluent treatment and discharge

The mill currently employs only primary effluent treatment. The excess suspended solids are removed from the effluent streams with two clarifiers. A portion of the paper machine clarifier underflow fibre is recovered back to the paper machines. The rest of the fibre is de-watered and disposed via landfill. Figure 2-2 shows a schematic representation of the effluent collection and treatment system.

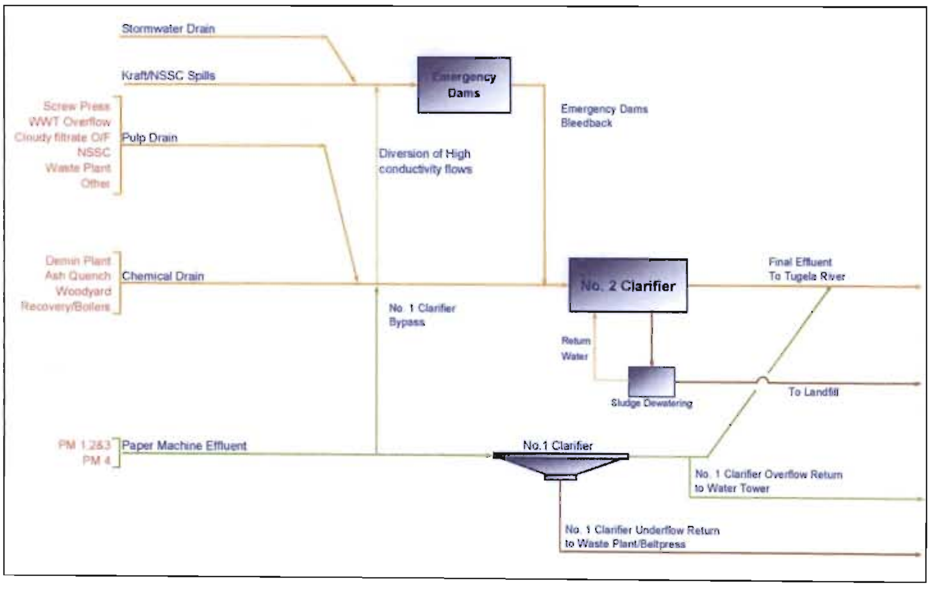


Figure 2-2 Schematic representation of the current effluent treatment system

The overflow from the two effluent clarifiers are combined and discharged to the river. The effluent volume is currently around 50 Ml/day (2080m^3/h).

Chapter 3 Literature review - Effluent recycling and re-use in the pulp and paper industry

3.1 Introduction (Edelmann, 1999)

In papermaking, water is used both as transport and processing medium. It is used as dilution water for chemicals, coolant in process equipment, seal water for vacuum pumps and for keeping equipment surfaces clean. Fresh water is introduced into the process mainly through paper machine showers, and is then re-used for various washing and diluting applications in the pulping and stock preparation sections.

As the process water is recycled, it comes into contact with dissolved organic and inorganic wood chemicals, as well as process chemicals added in the pulping and papermaking process. Suspended fibre and colloidal material also contaminate the water, limiting the re-usability of the water, hence becoming effluent, which has to be disposed to keep contaminant concentration from building up in process circuits.

In the 1950s, the solution for pollution was dilution. Through the years, mankind has become aware of their responsibility to the environment, and concepts such as sustainable development have become prevalent (Springer, 2001). According to South Africa's National Environmental Management Act, 1998, sustainable development is the integration of social, economic and environmental factors into planning, implementation and decision-making so as to ensure that development serves present and future generations. Sustainable development requires that pollution and degradation of the environment are avoided, or, where they cannot be altogether avoided, are minimised and remedied.

Webb (1998) states that sustainability for the pulp and paper industry includes:

- avoiding depletion of ground water levels.
- ensuring that wastewater discharges are of adequate quality.
- re-using process water as intensively as practicable, whilst not increasing the use of other non-renewable resources.

The modern trend is for industry to adopt the concept of a triple bottom line, where environmental and social considerations have to be taken into account together with the need to make profit (Springer, 2001).

During the last 20 years, large investments have been made worldwide by the pulp and paper industry to reduce the environmental load of paper production. However, the industry is still facing increasing environmental pressure from the public and the authorities (Edelmann, 1999).

Albert (1993) highlights the fact that mills often come into compliance, only to find that new environmental regulations are imposed. Stopgap measures implemented to meet older regulations are often not adequate to meet new regulations, and often major investments and equipment become redundant. This trend is driving mills to consider operating effluent-free, as this will release them from restrictive and costly environmental regulations.

Edelmann (1999) points out that due to the high capital-intensity of paper production, the paper industry is careful of adopting new concepts. Therefore, the targets set by industry for reducing fresh water consumption and effluent are:

- product quality and process runnability should be maintained or improved.
- pre-treatment concepts should not lead to increased chemical consumption.
- energy efficiency of papermaking should improve.
- system closure should lead to cleaner processes and better process management.
- environmental impacts should be reduced.
- the solution should not impair the competitiveness of the industry.

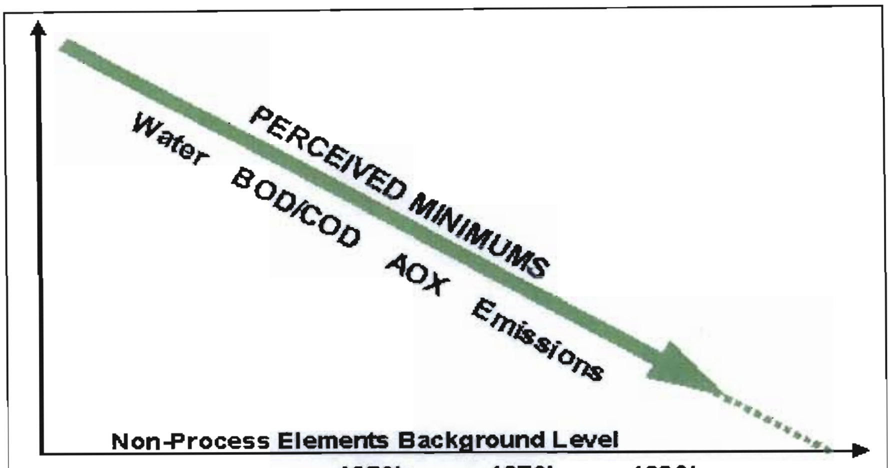
When evaluating the effects of closing water cycles in a mill, it is therefore important to use the process analysis tools that are available for the development of closed water cycles. These include process simulation and pinch analysis techniques, which are used as screening or detailed design tools for producing new process concepts for water re-use. These and other tools, together with conventional knowledge of the system, allow for the comparison and evaluation of different objective functions, such as investment and operational cost, energy consumption, effluent load and operational reliability.

3.2 The Minimum Impact Mill Concept

Elo (1995) defines a Minimum Impact Mill (MIM) as a mill that has minimised or eliminated all effluent streams, is a net producer of energy, and has air emissions to atmosphere consisting only of air, CO_2 and water vapour.

A MIM is perceived to have a minimum impact on the environment, based on the current level of understanding of 'minimum impact'. This can vary depending on the location of the mill – one mill discharging 50kg COD/ton pulp may be perceived to not have a significant environmental impact, whereas a mill elsewhere in the world discharging 5kg COD/ton pulp may be perceived to have a significant environmental impact. There are therefore many different levels of MIM, with the ultimate being a zero discharge mill.

Figure 3-1 shows how the perceptions of minimum impact have changed over the years.



	1950's	1970's	1990's
Effluent (m^3/ton)	> 200	100	< 50
BOD kg/ton	50	25	< 5
TRS kg/ton	5	2	< 0.1

Figure 3-1 Changes in the Minimum Impact Mill over time (Elo, 1995)

With the trend of legislation moving towards zero discharge for compliance, Elo (1995) contends that it is preferable to set the target to zero effluent discharge, and to determine what would be required to meet this target in a technologically and economically viable way.

Albert (1993) supports this view, and suggests developing a logical program to get from the existing to the ultimate configuration. This plan is implemented in phases, as new regulations are imposed or if the cost/benefit criteria change; therefore the processes that are used to ensure compliance also become building blocks toward the ultimate mill effluent treatment and discharge configuration.

3.3 Effluent reduction methods

In 2001, the European Commission released the Integrated Pollution Prevention and Control (IPPC) Reference Document on Best Available Techniques (BAT) in the Pulp and Paper Industry (IPPC, 2001). The IPPC document specifies that the conclusions on BAT are based on real-world examples and expert judgement of a technology working group. This document lists several technologies and practices as BAT. These range from cleaner production, internal recycling and external treatment and recycling.

3.3.1 Cleaner production

Riebel, (2002) cites the following as Best Available Techniques for cleaner production:

- Dry debarking

- Increased delignification before bleaching by extended or modified cooking and additional oxygen stages
- Efficient brown stock washing and closed cycle brown stock screening
- Elemental Chlorine Free (ECF) or Totally Chlorine Free (TCF) Bleaching
- Effective spill monitoring, containment and control

These options reduce both the effluent volume and the contaminant load.

Wiseman (1996) lists the following measures that can be followed to minimise freshwater use in a mill:

- Replacing packed glands on pumps with mechanical seals
- Restricting the use of freshwater for hoses
- Reviewing the performance and requirements for showers on the wet-end and press section.

All these options could significantly reduce the freshwater consumption of the mill.

3.3.2 Internal recycling

3.3.2.1 Paper machine white water re-use

Paper mills typically consume 15% to 25% of the total water in an integrated pulp and paper mill. This results in excess white water that can be re-used in the paper machine to minimise water use and effluent discharge (Panchapakesan, 1992). White water has high fibre content (Jordan, 1995), and has to be clarified before it can be re-used. The clarified filtrate can then be re-used to replace fresh water in the paper machine.

The following techniques are available for white water clarification (Jordan, 1995):

- Filtration
- Flotation
- Sedimentation

Typically, fibre recovery is achieved using a 'save-all', using a drum or disc filter (Wiseman, 1996). This process has little effect on BOD and COD concentrations in the filtrate, and no effect on inorganic dissolved solids. When recycling filtrate, this could lead to accumulation of these components in the white water system.

Therefore, closing a backwater system through white water filtration and re-use will only be successful in systems with little soluble material that can accumulate, or where the wet-end chemistry is simple and unaffected by the contaminant build-up. (Wiseman, 1996)

3.3.2.2 Other internal recycling techniques

The following are possible Best Available Techniques that involve internal recycling of effluent (Riebel, 2002)

- Stripping and re-use of contaminated condensate
- Collection and re-use of clean cooling and seal waters

The vacuum pump seal system is an area of high water consumption in the paper machine (Panchapakesan, 1992). This water can either be re-used in other applications, or re-circulated back to the vacuum pumps. Seal water can also be cascaded from the high vacuum pumps to the low vacuum pumps. The seal water is usually contaminated with fibre, and the temperature rises by about 12°C. Therefore, a heat exchanger or cooling tower may be needed to facilitate re-use of seal water (Jordan, 1995).

3.3.3 Effluent treatment and recycling

3.3.3.1 Effluent treatment for discharge

Traditionally, before being discharged, pulp and paper mill effluents are treated through methods that fall into the following groups (Jordan, 1995):

- Pre-treatment – equalisation, coarse screening, temperature control, pH control
- Primary treatment, usually clarification or dissolved air flotation (DAF), for removal of suspended solids
- Secondary treatment – biological treatment of the effluent to remove organic substances (BOD and COD). This may be aerobic or anaerobic processes.
- Physical-chemical treatment, for the additional removal of suspended solids, COD and colour.
- Handling and disposal of sludge generated in the various treatment stages.

Most mills employ primary treatment through clarification, which is generally considered a minimum requirement for all mills (Jordan, 1995). Cronin (1996) states that although primary and secondary treatment of effluent is generally suitable for river discharge, some type of tertiary treatment is usually required to enable recycling of effluent.

3.3.3.2 Effluent treatment for re-use

In closing up a water system, dissolved solids and organics can cycle up to levels that may cause operational problems such as corrosion, erosion, scale and deposits. To achieve

There is therefore an inherent trade-off between product quality and production cost on the one hand and reduction in water usage and effluent discharge on the other (Chen and Horan, 1998a).

3.4.1 Benefits of system closure

Any measure which decreases fresh water consumption will globally increase the temperature of the mill water cycles (Jordan, 1995). This has the benefit of lower steam consumption for the production of warm and hot water; better washing efficiency on the washers; better drainage in the paper machine wet-end; higher sheet dryness after the press section; higher temperature of the sheet entering the first dryer – hence less steam consumption.

Closing the mill's white water system has the following benefits (Panchapakesan, 1992):

- Minimised fresh water consumption
- Less chemical consumption
- Lower losses in fibre, filler and fines on the paper machine
- Reduced cost of heating white water
- Environmental compliance, through reduction in effluent volume, COD, BOD, TSS and TDS
- Reduced effluent treatment cost

3.4.2 Drawbacks of system closure

Berard (2000) lists the following as problems associated with paper mill closure:

- Wet end deposition
- Mill odour
- Foam and corrosion
- Product odour
- Decreased machine runnability
- Drainage loss
- Retention loss

Temperature also plays a significant role in the wet-end chemistry and its associated problems (Berard, 2000). Temperatures can reach 40-55°C with water closure. This temperature modifies the microbiological population, increases the tackiness of some deposits and increases the scaling potential of calcium carbonate.

At high temperatures, the microbiological activity in the system increases (Wiseman, 1996). Anaerobic activity can generate volatile fatty acids that cause unpleasant odours. Slime forming bacteria grow in mats, which are carried through the system, blocking pipes and sprays. It may also cause streaks in the product. Organic acids produced by biological activity can significantly modify the pH of the system and thereby affect the wet-end chemistry.

Mehta (1996) and Panchapakesan (1992) also mention the build-up of fines and ash content in the furnish as a risk factor when re-using white water in a paper machine.

Gleadow *et al.* (1994) states that recycling of effluent may lead to changes in solubilities with the differing acidity, alkalinity and temperature in the system. This could lead to scales and deposits. Chemical consumption in the system may also increase. Organic substances may act as surfactants that hinder settling and clarification operations. Furthermore, chelants used for metals control in one area of the mill may carry contaminants to another area of the mill.

3.5 Cost vs. Legislation for effluent reduction

Elo (1995) states that the investment required to achieve a minimum impact mill (MIM) has to be balanced with the returns on that investment. There has to be a balance between environmental benefits, profitability and viability of the industry, as investing money without any measurable return is not good business.

Elo (1995) also maintains that, as environmental compliance is a moving target, it is desirable to set the effluent discharge target to zero. This leads to the development of a roadmap to MIM, with the ultimate being zero discharge. Lagacé (1998) further states that by progressively closing a mill water system, the costs are incurred over a longer time period. In addition, some of these costs would have been incurred through maintenance and equipment upgrade costs, regardless of whether the mill was closing its water circuits. Therefore, a gradual approach to mill closure reduces the economic impact on a mill.

Wiseman (1996) states that the paper manufacturing industry is inherently capable of running at zero liquid effluent (ZLE) discharge. However, the challenge is to run at ZLE discharge and stay in business.

Environmental challenges are increasingly subtle, and therefore may have a more dramatic influence on the economic side of the business. Meeting these challenges will require approaches that build on the facility's existing equipment, minimising the capital required to succeed (Vice, 2002).

Vice (2002) states that industry needs an environmental policy that promotes opportunities for pollution prevention through economically driven tools. Tools, such as process integration, that link economics and environmental impact, will allow industry to capitalise on effluent reduction opportunities rather than taking a short-sighted, high capital cost approach to meet command-and control end-of-pipe requirements.

Dexter (1996) contends that current environmental regulations deter innovation. However, water re-use and closure represents a competitive advantage, using resources more efficiently in an increasingly environmentally conscious market.

Vice (2002) suggests that bringing industry's technical realities to government's attention in a manner that recognises government constraints, but does not compromise business objectives, will help in the establishment of effective environmental regulations in future. The challenge to government is therefore to develop a policy that encourages development of technical solutions that will achieve environmental, economic and social objectives that can be met in the most cost-effective way possible.

3.6 Techniques for optimal effluent reduction and re-use

The main steps in the development of closure strategies in a mill are (Paris, Dorica, Francis and Orccotoma, 1999):

- Computer simulation of mass and heat balances for the current mill operation
- Analysis of pulp and whitewater networks, including water quality requirements and potential sources
- Development and simulation of potential closure scenarios
- Evaluation of the effects of process modifications on manufacturing operations, process economics and product quality

Computer simulation is essential for the development and implementation of feasible designs (Paris *et al.*, 1999). It can be used to reduce the costs and risks involved with closure, and help guide implementation.

Mansfield and Böhmer (2003) cite the benefits of using computer simulation for finding water re-use solutions:

- Computer simulation can be used to simulate complex systems, such as an entire mill.
- All technologies are evaluated on the same basis – the baseline mill model. This improves the confidence level in the ultimate solution.
- Computer simulation eliminates subjectivity and often refutes solutions that initially seem viable.

- Because of the high level of process detail, the computer simulation accounts for and highlights process interactions that are not always apparent using simple mass balances.
- The baseline model can be continually updated to reflect process changes, such as production increases or the installation of new equipment.
- Computer simulation can quantify the effect of recycling on effluent temperatures, thus enabling optimum placement of heat exchangers and cooling towers within the mill.
- Computer simulation predicts in-mill and final effluent qualities and quantities, thus providing input data for cost calculations.
- Computer simulation is used to determine the optimum sequence of effluent treatment implementation, but also makes provision for partial implementation.
- Computer simulation can be used to perform a sensitivity analysis on the final solution, thus identifying areas where a higher level of accuracy is important. If deemed necessary, further investigation may then be done in these areas to improve the confidence level in the ultimate solution.

Figure 3-3 shows the simulation steps used to help find an effluent management solution for a mill (Mansfield and Böhmer, 2003).

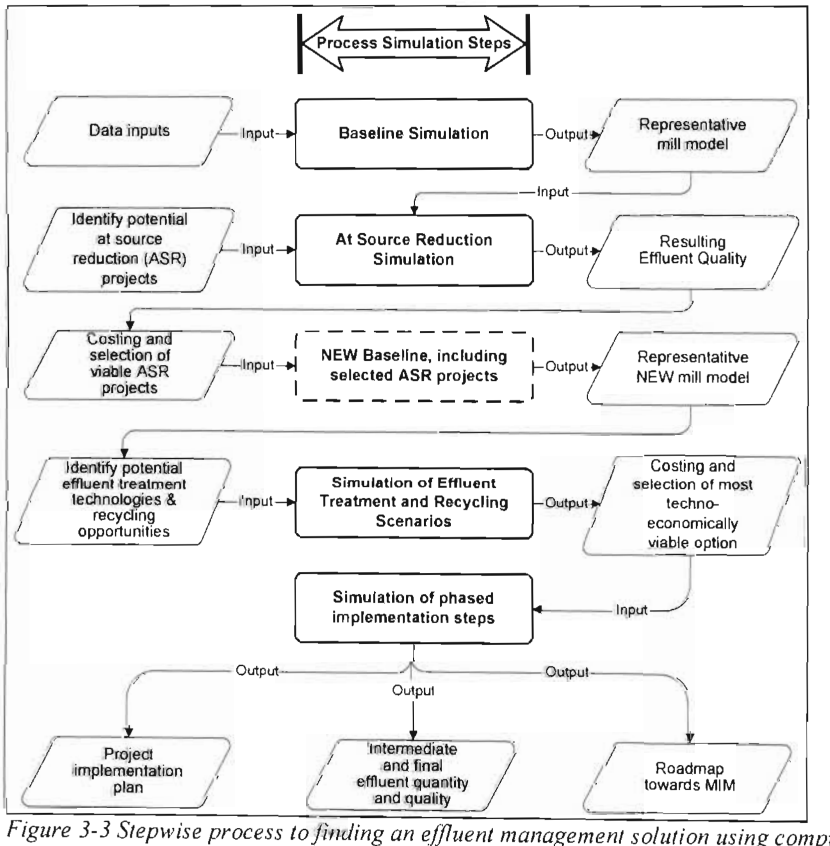


Figure 3-3 Stepwise process to finding an effluent management solution using computer simulation (Mansfield and Böhmer, 2003)

Paris *et al.* (1999) mentions the use of network analysis, analogous to thermal pinch analysis, to establish a white water network that will minimise fresh water requirements whilst respecting process constraints. There are various tools like pinch analysis that can be used in the development of closed water cycles (Edelmann, 1999).

Using economic tools, such as process integration, to explore ways to make an existing mill produce more with a better cost structure helps integrate all cost flows, whilst minimising losses. Cost effectively embedding environmental plans into the mill's capital plans through process integration involves looking at all elements that have an environmental and economical cost, and working to minimise both (Vice, 2002).

3.7 Conclusion on effluent treatment and re-use

The pulp and paper industry is facing stricter environmental challenges, forcing mills to reduce fresh water consumption through treatment and re-use of process waters. Considering the fact that regulations will only get stricter, it is logical for mills to target zero effluent discharge, and developing a roadmap for achieving this target over time.

Tools such as process simulation and process integration can be used to optimise environmental solutions to maximise the environmental benefit achieved whilst still being economically viable and sustainable.

By setting legal standards that are both environmentally and economically viable, government will encourage mills to be innovative in developing environmental solutions, rather than merely opting for minimum compliance. Process integration techniques may help to achieve this goal by demonstrating that environmental solutions could benefit both the mill and the environment, depending on the regulations.

Chapter 4 Literature review – Process Integration

4.1 Introduction (Bédard, Sorin and Leroy, 2001)

Process integration is a term used for the application of methodologies aimed at designing a new facility or modernising an existing facility by looking at the system as a whole and optimising the connections between its units rather than improving the units itself. Process integration techniques provide a basis for developing and analysing designs in their entirety, and can be readily focused on pollution prevention objectives (Buehner and Rossiter, 1996).

Process integration started in the late 1970s with the concept of thermal pinch technology. In this method, thermodynamic principles were used to determine targets – the minimum requirements of hot and cold utilities in the system. These targets were then used to set up a design network of heat exchangers to achieve the targets. The pinch approach has since been expanded to mass exchange networks, which include industrial water network optimisation.

There are two groups of methods for the systematic design of water re-use networks. The first are graphical methods based on the pinch analysis technique, and it allows for targeting and design of water networks. The second group of methods uses numerical optimisation techniques to find the optimal re-use scheme for a plant. Numerical methods can also account for plant layout constraints, and capital and operating costs, and can therefore identify the optimal arrangement of distributed water treatment systems.

This literature review gives an overview of both graphical and numerical approaches to process integration.

4.2 Overview of process integration

The concept of pinch technology as a tool for heat exchanger network design emerged in the late 1970's. With the use of targets derived from pinch analysis, thermally efficient optimal designs could be achieved. Targeting is done by constructing composite curves from hot and cold stream data. By plotting temperature versus enthalpy of the process streams, a graphical representation of the mass and heat balance of the system is obtained. When the two composite curves are fitted together, a 'pinch point is located, and the minimum hot and cold utility targets are obtained. Figure 4-1 shows the hot and cold composite curves for energy targeting. The shaded area indicates areas where process-to-process heat recovery is possible. The minimum hot and cold utility and the pinch point are also indicated. The composite curves set the targets before design (Linnhoff, 1993 and Buehner and Rossiter, 1996).

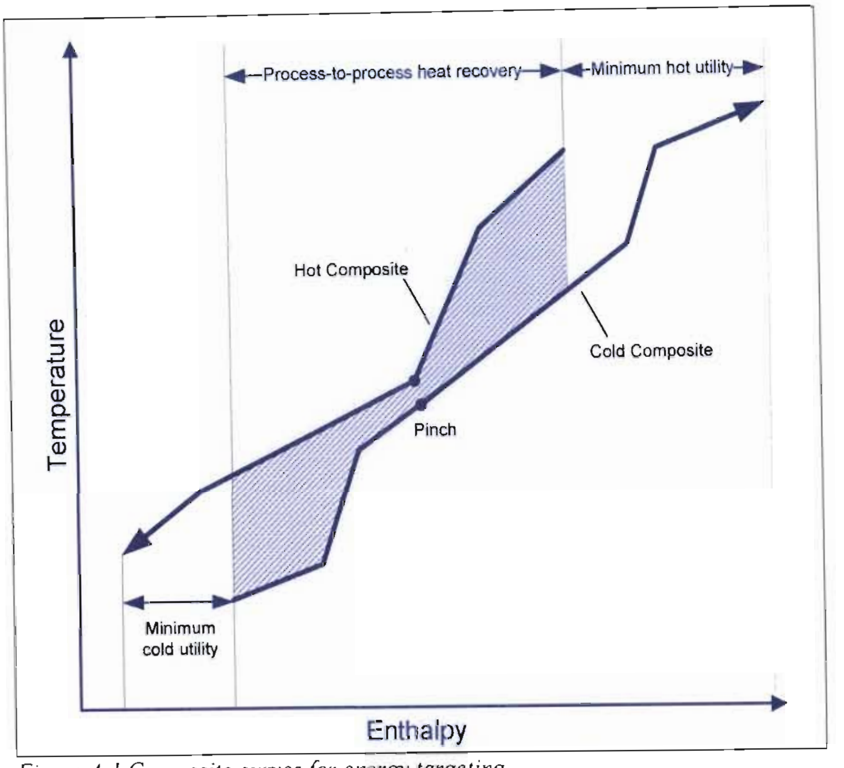


Figure 4-1 Composite curves for energy targeting

Linnhoff and Hindmarsh (1983) developed a pinch design method to allow for the design of a heat exchanger network (HEN) using the targets obtained from the composite curves. The pinch principle states that no design can achieve the utility targets if there is any cross-pinch heat transfer from above the pinch to below the pinch.

El-Halwagi and Manousiouthakis (1990) identified a useful analogy between the synthesis of heat exchanger networks (HENs) and mass exchanger networks (MENs). They developed an algorithmic procedure for the automatic synthesis of MENs. This procedure is based on a mixed integer linear programming (MILP) formulation that generates MENs featuring the minimum number of heat exchangers, subject to the minimum cost of Mass Separating Agents (MSA). A MSA is a lean stream used in a unit operation such as a distillation column or liquid-liquid extraction.

Hallale and Fraser (1998) proved that targeting the minimum number of units does not necessarily lead to the minimum cost. They then developed a new graphical technique for capital cost targeting for MENs, based on the minimum number of trays. They also developed a design method that allows the targets to be closely approached (Hallale and Fraser, 1998, 2000a and 2000b).

Takama, Kuriyama, Shiroko and Umeda (1980) looked at water reduction in a total system consisting of water-using units and wastewater-treatment units. They also introduced the concept of a general system structure, called a superstructure. The problem of maximising water re-use is considered as a problem of optimising water allocation in a total system. They use a mathematical programming approach, but transform the problem to a series of problems without inequality constraints by including a penalty function, which eliminates the initial problem of searching for feasible points. This work set the stage for the use of pinch technology to minimise water and wastewater – either through graphical or numerical methods.

Wang and Smith (1994a) developed a graphical method to target and design for minimum wastewater for water re-use, regeneration re-use and regeneration recycling. They introduced the concept of the limiting composite curve and minimum water supply line. The method also looked at multi-contaminant processes. Wang and Smith (1995) later expanded this work to processes with fixed flowrate requirements, processes with water losses and processes with multiple sources of freshwater. However, the design method proposed by Wang and Smith (1994a) is complex, and involves breaking loops in the design network (Bagajewicz, 2000).

To overcome the difficulty of loop breaking, Olesen and Polley (1997) presented a new design procedure for the method developed by Wang and Smith (1994a) for single contaminant problems. Kuo and Smith (1998a and 1998b) also developed new graphical approach to simplify the design methods of Wang and Smith (1994a and 1995). The new methodology offers better process configurations for regeneration re-use and regeneration recycle designs.

Wang and Smith 1994b developed a method to design distributed effluent treatment systems. The aim of this work is to minimise cost by minimising the flow treated. Analogous to the method developed by Wang and Smith (1994a), they construct an *effluent composite curve,* to which an effluent treatment line is fitted to obtain a minimum treatment volume target. They presented design rules for the treatment target to be achieved, and developed a method for designing the distributed effluent network. The method was also expanded to multiple-contaminant systems. Kuo and Smith (1997) expanded on the distributed effluent treatment design first reported by Wang and Smith (1994b). They also used a superstructure and mathematical techniques for solving multi-contaminant problems. However, the superstructure is simplified with insights obtained through graphical targeting.

Castro, Matos, Fernandes and Nunes (1999) re-worked the Wang and Smith (1994a, 1994b and 1995) method and introduced the concept of multiple pinches. This prevents the design of networks that do not lead to minimum-cost distributed effluent treatment systems.

Dhole, Ramchandi, Tainsh and Wasilewski (1996) introduced the concept of the two-composite plot, which plots water sources and water demands in terms of purity on the y-axis, and flow on the x-axis. They explain how the plot can be used to find freshwater and wastewater targets and help with the network design. This process, called WaterPinch, is combined with numerical techniques to give a solution to the problem.

Hallale (2002) reviewed the method of Dhole *et al.* (1996), and noted that the two-composite plot representation is not a true reflection of the target, as mixing of water sources can change the shape of the source composite plot, and hence the targets. The two-composite plot is therefore not a true targeting approach, but rather a graphical representation of a particular design that has been obtained through mathematical programming.

Hallale (2002) then introduced the concept of a Water Surplus Diagram as an alternative targeting approach to that of Dhole *et al.* (1996). A design procedure is also developed for this targeting method. Hallale (2002) notes that multiple-contaminant problems should rather be approached using mathematical programming techniques.

Doyle and Smith (1997) presented linear (LP) and non-linear (NLP) mathematical formulations for targeting water re-use with multiple contaminants. They overcame the difficulty of non-linear programming by presenting a combined LP and NLP approach. They proposed that the NLP problem can be solved by first solving the linear model to provide initial values for the NLP optimisation.

Based on the work by Doyle and Smith (1997), Alva-Argáez, Kokossis and Smith (1998a and 1998b) developed an automated method for synthesis of industrial water systems with regeneration. In this method, the outlet concentrations are set to a maximum and the treatment unit concentrations to zero. They also include capital and operating cost as well as the sum of the model errors in the objective function. This means that running the linear program will drive the error to zero. The series of linear optimisations will therefore converge to the NLP solution.

Galán and Grossman (1998) developed a mathematical model for distributed wastewater networks. The model gives rise to a non-linear, non-convex problem. This type of model can lead to local optima rather than a global optimum being found and can also cause convergence difficulties. They therefore proposed a search procedure which involves the sequential solving of a relaxed linear model (MILP) and a non-linear model (MINLP). This method yields global or near-global optimum solutions. In this approach, GAMS is used to set up and solve the MILP and MINLP models. Huang, Chang, Ling and Chang (1999) followed a similar NLP procedure for determining the least amount of freshwater consumption and minimum wastewater treatment capacity. The method is also used to synthesize the resulting water usage and treatment network.

Jödicke, Fischer and Hungerbühler (2001) developed a MILP method for rapid screening of designs that minimises the sum of the operating and investment cost, even when the contaminant concentration may be unavailable. This approach can be used when data is limited, but the system and its limits are well understood.

Feng and Chu (2004) outlined a methodology for assessing the economic performance of industrial wastewater re-use systems including wastewater treatment. The freshwater and wastewater disposal cost savings has to be balanced against the cost of wastewater regeneration and re-use.

4.3 Graphical approaches to pinch analysis (Wang and Smith, 1994a)

Wang and Smith (1994a) define three possibilities for treating wastewater:

- Re-use - Wastewater is re-used directly in other operations in the process. Re-use may require blending wastewater from one process with wastewater from another process and/or freshwater. Re-use of wastewater in the same process is not allowed.

- Regeneration-re-use – Wastewater can be regenerated by partial treatment to remove contaminants that prevent its re-use. This regenerated water can then be re-used in other operations. Blending with other wastewater and/or freshwater may also be required. Re-use in the same process is not allowed.

- Regeneration recycling – Wastewater can be regenerated to remove contaminants which have built up, and is then recycled. Treated water may enter processes in which it has previously been used.

Wang and Smith (1994a) developed a method to target and design for minimum wastewater for the above three cases.

4.3.1 Limiting water profile

For a given process, as shown in Figure 4-2, the process lines can be plotted on a concentration versus mass load graph. This is analogous to the heat pinch method of plotting temperature versus enthalpy (Linnhoff and Hindmarsh, 1983). Wang and Smith (1994a) introduced the concept of a limiting water profile, where the water used in the process is at maximum possible inlet and outlet concentration, and hence at minimum flow for the maximum inlet concentration.

Any water profile below the limiting water profile will satisfy the process requirements. The maximum inlet and outlet concentrations are set by the user for practical reasons such as:

- To avoid precipitation of contaminants

- To avoid fouling of equipment
- Corrosion limitations
- Minimum flowrate requirements to avoid settling of solid materials
- Solubility constraints

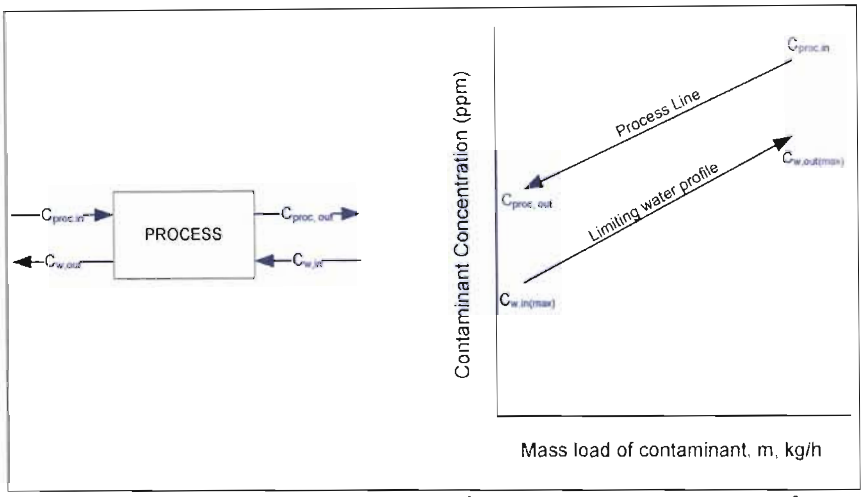


Figure 4-2 A water using process, represented as concentration versus mass of contaminant transferred. Maximising the water inlet and outlet concentrations defines the limiting water profile (Wang and Smith 1994a).

4.3.2 Re-use

Wang and Smith (1994a) constructed a limiting water composite curve for a system with more than one process, using the maximum water inlet and outlet constraints set by the user (Figure 4-3). The limiting water profile for the system is then matched with a water supply line. This water supply line represents the minimum water flow required to satisfy all concentration restrictions of the system (Figure 4-4). This sets a flow target for design.

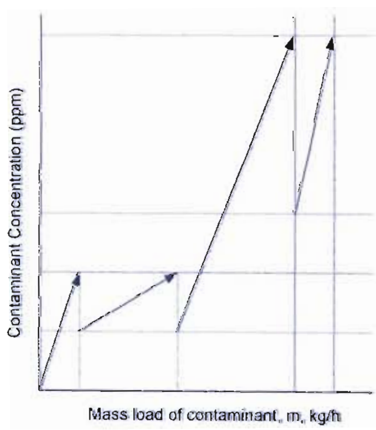


Figure 4-3 Limiting water profiles

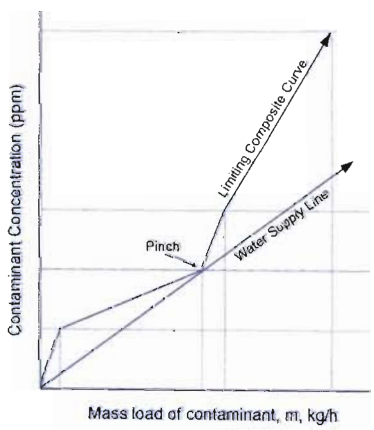


Figure 4-4 Limiting composite curve, matched with a water supply line

For this minimum water supply target to be meaningful, a design is needed in which the target flowrate and all other concentration restrictions are met. Wang and Smith (1994a) then expand on the methods introduced by El-Halwagi and Manousiouthakis (1989 and 1990) to set up a network design.

They do this by minimising the number of water sources, thus ensuring that as few as possible matches are made. This involves bypassing and mixing to minimise the number of matches.

This method was also expanded to multi-contaminant systems.

4.3.3 Regeneration re-use

Wang and Smith (1994a) define a regeneration process that has to perform to either of the following:

A minimum outlet concentration of C_o, therefore

$$C_{out} \leq C_o$$

A removal ratio R.

$$R = \frac{f_{in}C_{in} - f_{out}C_{out}}{f_{in}C_{in}}$$

If a regeneration process is used, the water supply line will be as shown in Figure 4-5. The water is taken to a concentration C_{REGEN}, up to the limiting composite curve. It then enters the regeneration process, which brings the level of contaminant down to C_0 The rest of the mass transfer is completed with regenerated water, at the same flowrate as before regeneration.

From Figure 4-5, it is clear that regeneration reduces flowrate. Figure 4-6 shows the composite water supply line for regeneration. Clearly, the composite supply curve can be minimised further if the concentration at which regeneration takes place is increased.

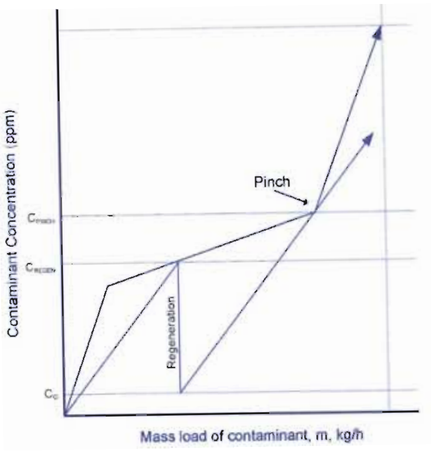


Figure 4-5 Regeneration of wastewater reduces the flowrate of wastewater and freshwater

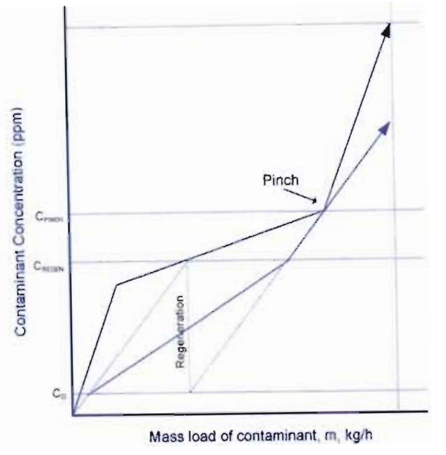


Figure 4-6 Composite water supply line

Figure 4-7 shows the water supply line when water is regenerated at the pinch concentration. Although the water supply line crosses the limiting composite curve, it is not infeasible, as the composite water supply line does not cross the limiting composite curve (Figure 4-7). From Figure 4-7 it is clear that the composite water supply line for regeneration has been minimised.

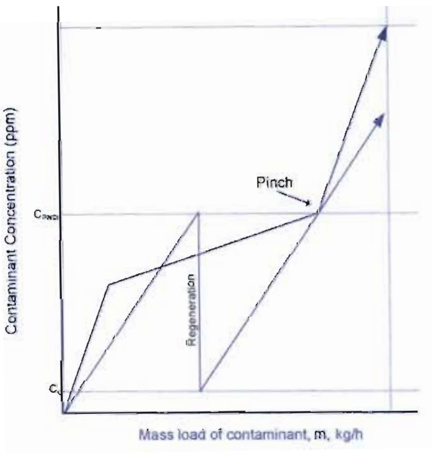


Figure 4-7 Regeneration of water at pinch concentration

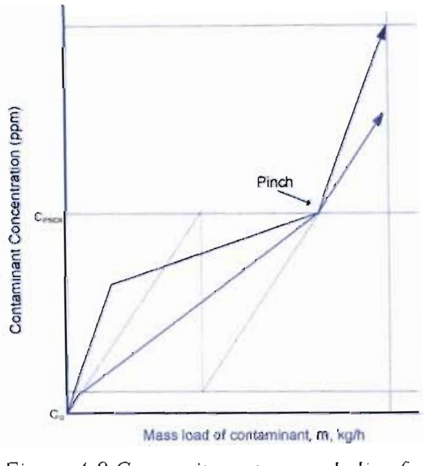


Figure 4-8 Composite water supply line for regeneration at pinch concentration

The water flowrate cannot be reduced below the flowrate obtained in Figure 4-7, as a lower flowrate would cause the composite water supply line to cross the limiting composite curve.

If the water is allowed to go beyond the pinch concentration before regeneration, at the same flowrate as in Figure 4-7, the water supply line is as in Figure 4-9. The composite water supply line in Figure 4-10 indicates that the flowrate is still minimised. However, the slope above the pinch concentration is lower than in Figure 4-7. This means that some unnecessary regeneration has been done.

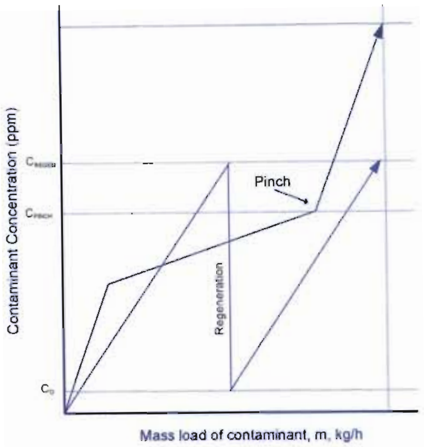


Figure 4-9 Regeneration of water above pinch concentration

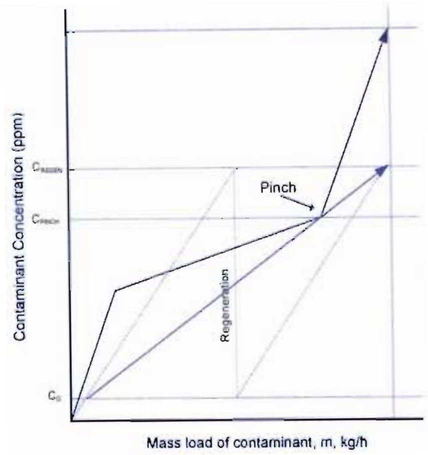


Figure 4-10 Composite water supply line for regeneration above pinch concentration

It is therefore clear that allowing the water supply line to reach the pinch concentration before regeneration achieves two criteria simultaneously for regeneration re-use:

- Minimum water flowrate
- Minimum concentration reduction in regeneration process

Wang and Smith (1994a) then proceed to develop a method for designing for regeneration re-use, and also expand the method to multi-contaminant problems.

4.3.4 Regeneration recycle

If recycling is allowed, the flowrate can be reduced below that shown in Figure 4-7. The flowrate is then dictated by the flowrate below C_0 on the limiting composite curve, as shown in Figure 4-11. From Figure 4-11 there is clearly not enough water to satisfy the problem. The flowrate after regeneration therefore needs to be increased, which can only be done through recycling. Figure 4-12 shows the composite water supply line before and after regeneration.

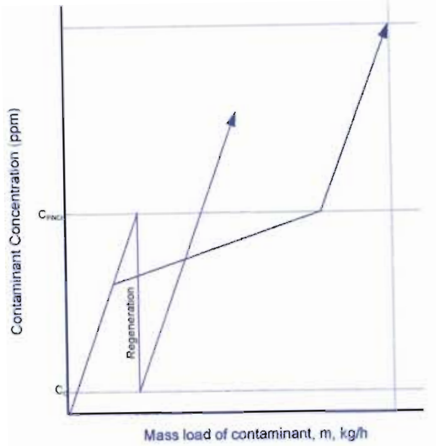


Figure 4-11 Minimum flowrate dictated by the slope of the limiting composite curve

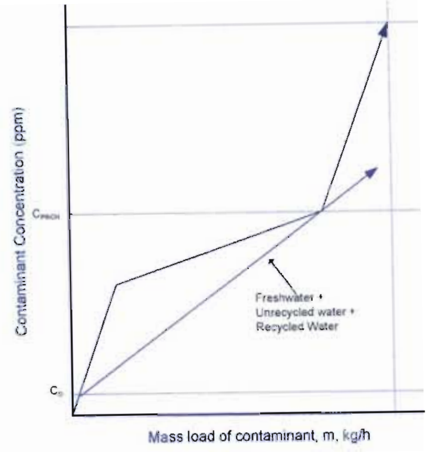


Figure 4-12 A composite of the water supply before and after regeneration

4.3.5 Effluent composite curves for distributed effluent treatment

Wang and Smith (1994b) adapted the approach developed in Wang and Smith (1994a) to enable the targeting and design of distributed effluent treatment systems.

If several wastewater streams have to be treated to a certain effluent concentration, C_e, the contaminant mass removed from each stream is given by

$$\Delta m_i = f_i (C_i - C_e)$$

Where:

f_i is the flowrate of stream i

C_i is the effluent stream inlet concentration

C_e is the environmental concentration limit

Using this equation, each effluent stream can be plotted in terms of concentration versus mass load, as shown in Figure 4-13. A composite effluent curve can be constructed using the effluent stream starting concentrations as concentration intervals. Figure 4-14 shows the resulting composite effluent curve. This effluent composite curve can be used to find effluent treatment targets.

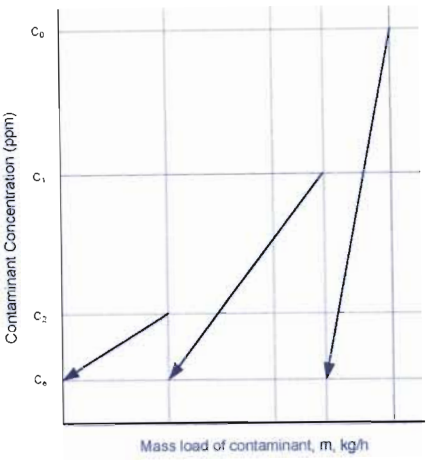


Figure 4-13 Wastewater streams

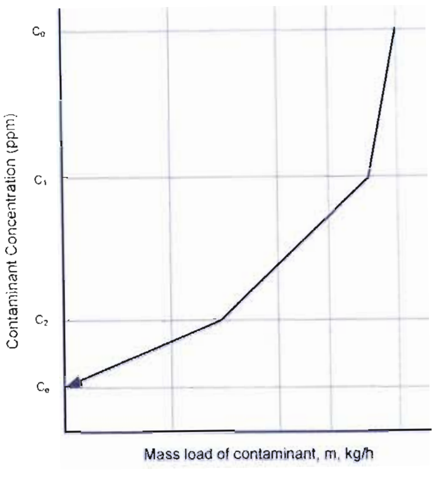


Figure 4-14 Composite effluent curve

For the treatment plant, the removal ratio R is defined as:

$$R = \frac{f_{in}C_{in} - f_{out}C_{out}}{f_{in}C_{in}}$$

If all treatment units have the same removal ratios, the minimum flowrate for treatment, f_{min}, can be found by fitting a treatment line to the effluent composite curve, as shown in Figure 4-15. The total contaminant mass to be removed is equal to that removed with the treatment process. The treatment line may not cross the effluent composite curve.

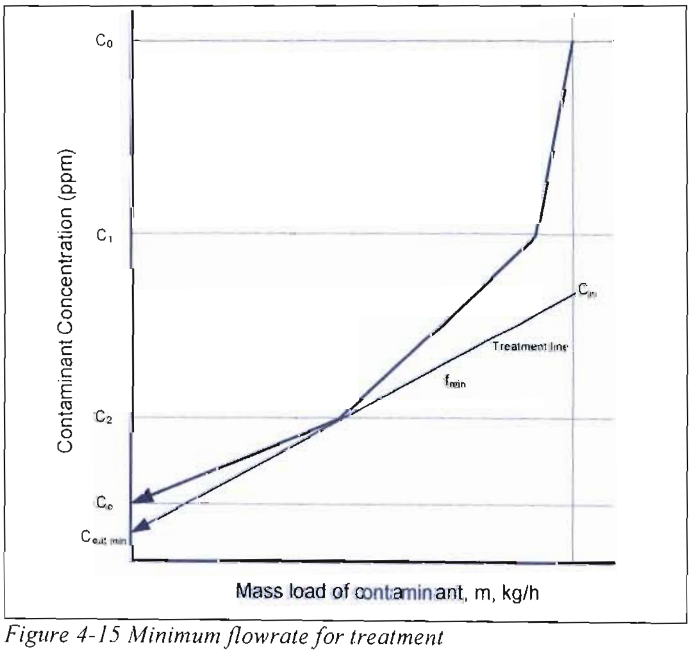


Figure 4-15 Minimum flowrate for treatment

Kuo and Smith (1997) use the effluent treatment curve to design a composite treatment targeting curve for treatment units with different removal ratios (R). Figure 4-16 shows the effluent composite curve, matched with two treatment plant lines (TP1 and TP2). The inverse of the slopes of the treatment lines are the required treatment unit flowrates of the respective treatment units. Using this flowrate together with the removal ratio, the inlet and outlet concentrations and mass removal rate (m_l) can be obtained. In each case, the treatment unit capacity has been minimised. Even though the TP2 targeting line crosses the effluent composite curve, when a composite treatment targeting curve is constructed as in Figure 4-17, the curve does not cross the effluent composite curve and hence the target is feasible.

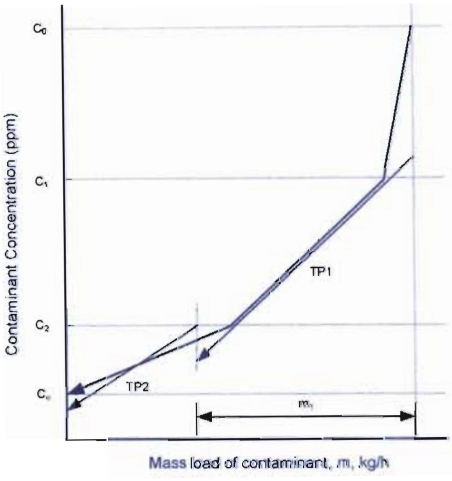


Figure 4-16 Composite effluent curve, matched with two treatment plant lines

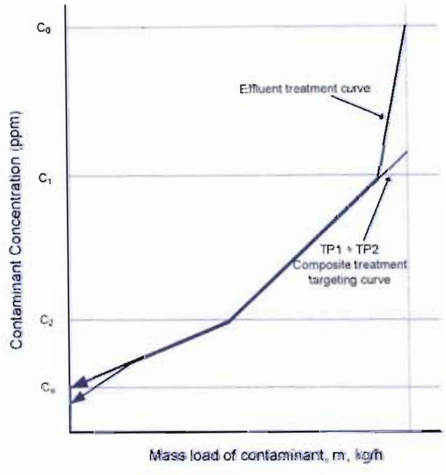


Figure 4-17 Composite effluent curve and composite treatment targeting curve

The design shown in Figure 4-17 is only one of many possible designs. Kuo and Smith (1997) propose that instead of optimising a single design obtained from targeting, that the target itself be optimised. This can be done by varying m1 and thus the fraction of the mass load removed by each treatment process. Using the resulting treatment process flowrate for each value of m_l, the total cost can be estimated for each value of m_l. This way, an optimum cost target can be obtained before design, thus ensuring a feasible design at minimum cost.

4.3.6 The two-composites plot (Dhole *et al.*, 1996)

Dhole *et al.* (1996) developed a new approach, where every unit operation or utility is considered to have aqueous input and output streams. There can be several inputs and outputs in a single operation. The input aqueous streams are plotted in a 'demand composite curve', on a graph having purity on the vertical axis, and stream flowrate on the horizontal axis. This demand composite defines the water demands in terms of required input purity for the overall plant.

Similarly, the output streams can be plotted to construct a 'source composite' for the plant in terms of the minimum output purities of the individual streams.

Figure 4-18 shows a plot with a source composite and a demand composite curve. The two curves are overlapped to define a pinch point between the two composites.

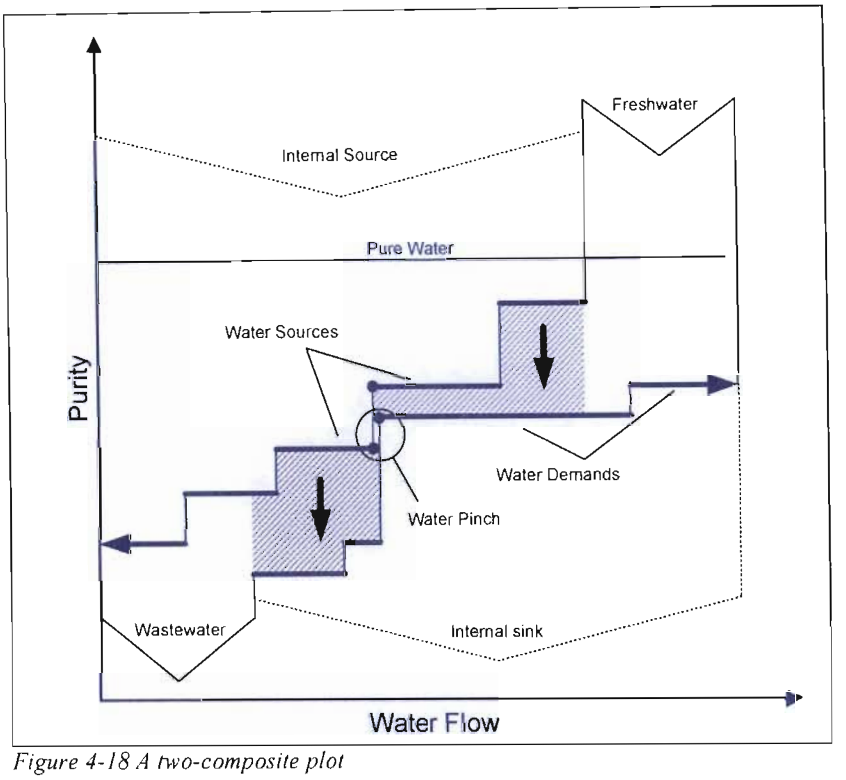


Figure 4-18 A two-composite plot

The overlap between the source and demand composites (shown by the shaded region) is the scope for re-use in the system. The available overlap is restricted by the pinch point between the source and the demand composites. The minimum freshwater requirement and wastewater flowrate is also shown in Figure 4-18.

The plot helps to identify design improvements. Sources above the pinch should be used to satisfy demands above the pinch, as transferring water across the pinch will exceed the minimum flowrate design target. Freshwater should not be used to satisfy demands below the pinch and sources above the pinch should not be sent to waste treatment.

The plot can also provide specific guidelines on how to maximise re-use of water. In Figure 4-19, the output streams from processes A and B are mixed. The resulting stream is sufficiently pure to satisfy the demand of process C. Therefore, the existing pinch point is relieved, and the two composite plots can be overlapped further, thus reducing freshwater and wastewater of the process. Figure 4-20 shows the resulting design for the system.

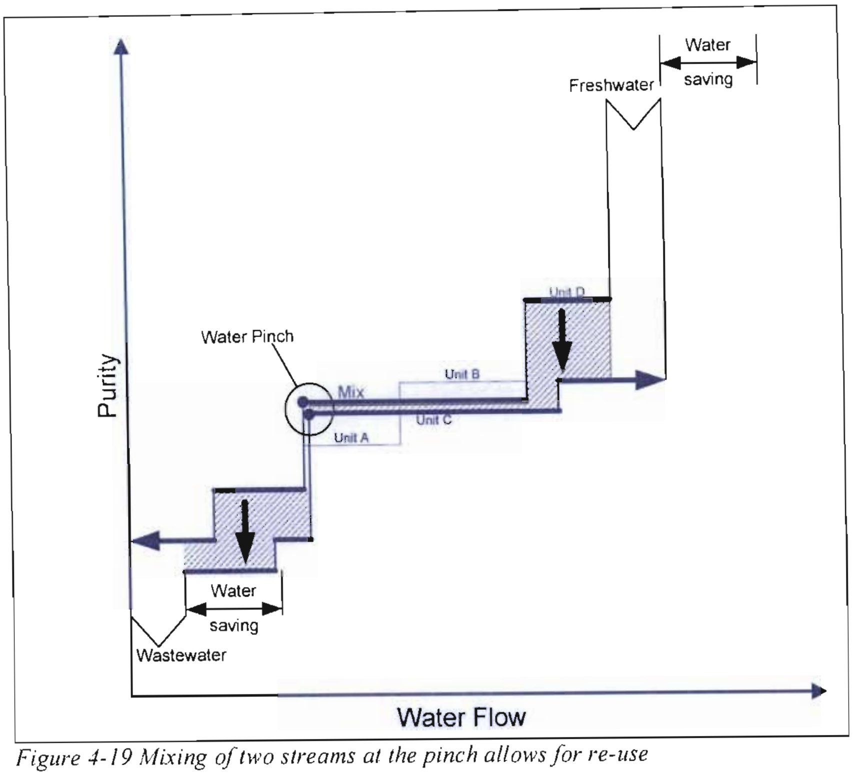


Figure 4-19 Mixing of two streams at the pinch allows for re-use

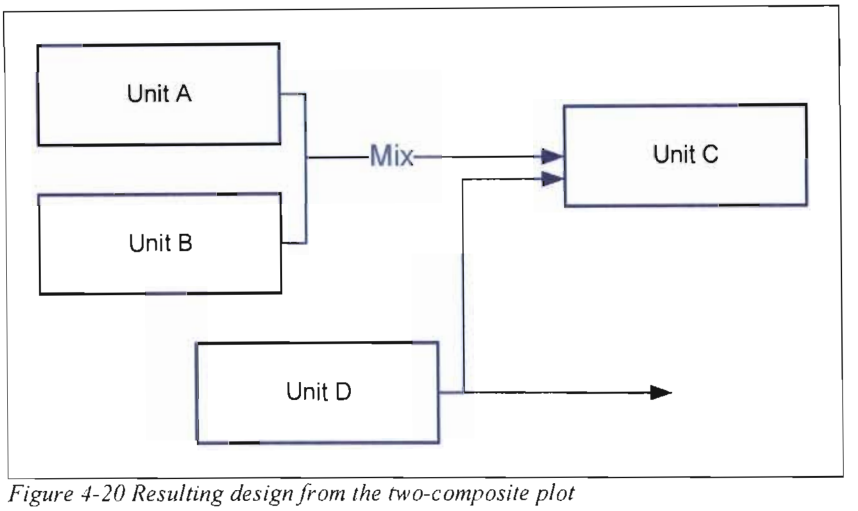


Figure 4-20 Resulting design from the two-composite plot

This method has been trademarked WaterPinch. and is also available as a mathematical programming tool. The mathematical tool. involving mixed integer non-linear programming algorithm allows the user to handle complex, multi-contaminant problems. The mathematical tool allows for the solving of the problem, whereas the visual tool may be used to view and conceptualise the results (Buehner and Rossiter, 1996).

4.4 Numerical approaches to process integration

The mathematical programming approach to design, integration and operation problems consists of three major steps (Grossman, Caballero and Yeomans, 1999). They are:

- The development of a representation of alternatives from which the optimum solution is selected (*superstructure*).
- The formulation of a *mathematical program*, generally involving discrete and continuous variables, for the selection of the configuration and operating levels.
- The *solution* of the optimisation model from which the optimal solution is determined.

4.4.1 Superstructure

Takama, Kuriyama, Shiroko and Umeda (1980) formulated a superstructure representation to describe a system comprising of water-using and wastewater treatment subsystems (Figure 4-21). Figure 4-22 shows the general structure of the system. A source of freshwater is provided to every subsystem, and an effluent stream from every subsystem is sent to an effluent discharge point. Each subsystem has a mixing and a splitting point. Flow from any splitting point is sent to every mixing point. The overall problem can then be defined to determine both design variables of subsystems and structure variables. This leads to a mathematical programming problem.

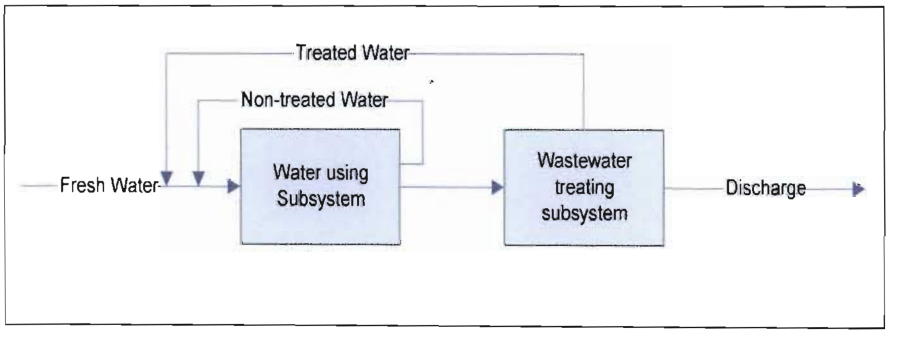


Figure 4-21 System for water use and treatment

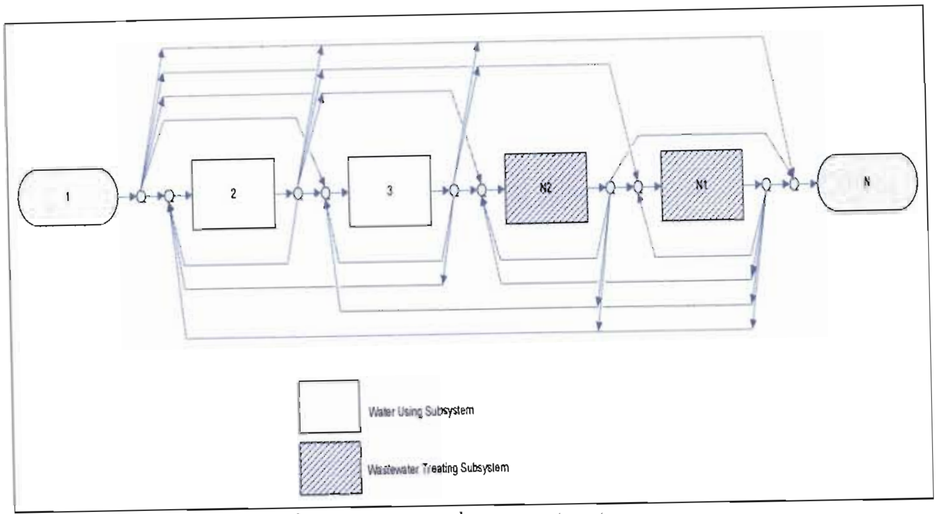


Figure 4-22 Superstructure for water use and treatment system

4.4.2 Mathematical programming (Grossman *et al.*, 1999)

Design and synthesis problems give rise to discrete or continuous optimisation problems. When represented in algebraic form, these form mixed-integer optimisation problems, having the following form:

$$\min Z = f(x, y)$$

subject to

$$h(x, y) = 0$$
$$g(x, y) \leq 0$$
$$x \in X, y \in \{0,1\}$$

Where

$f(x, y)$ is the objective function that has to be minimised

$h(x, y) = 0$ are equations that describe the performance of the system, such as mass balances and design equations.

$g(x, y) \leq 0$ are inequalities that define the constraints for feasible choices

Variables x are continuous variables of state, and y variables are discreet variables, generally restricted to 0-1, which defines the selection of an item or an action. This form of programming is called mixed integer programming (MIP).

If all functions are linear, the problem is a mixed integer linear programming (MILP) problem. If any of the functions are non-linear, the problem is a mixed-integer non-linear programming (MINLP) problem. If there are no 0-1 variables in the problem, it is either a linear programming (LP) or a non-linear programming (NLP) problem, depending on whether the functions are linear or not.

Solving a mathematical programming problem involves a search procedure for the minimum (or maximum) value of the objective function, subject to the system model and restrictions. Most commercial software packages can obtain a global solution for LP and MILP problems; however, no commercial package is guaranteed to find a global optimum solution for NLP and MINLP problems (El-Halwagi, 1998).

4.4.3 Solving techniques

There are several solution strategies that can be followed for the optimisation of mathematical models for design and synthesis. The two major strategies are simultaneous optimisation and sequential optimisation. In simultaneous optimisation, a single model is optimised at once. The process is rigorous, as all trade-offs are taken into account simultaneously. The sequential optimisation approach involves solving a sequence of sub-problems, usually in increasing level of detail. The reason behind sequential optimisation is to avoid solving a large problem (usually MINLP) (Grossman *et al.*, 1999).

Takama *et al.* (1980) used a mathematical programming solving approach, but transformed the problem to a series of problems without inequality constraints by including a penalty function, which eliminates the initial problem of searching for feasible points.

Doyle and Smith (1997) overcame the difficulty of non-linear programming by presenting a combined LP and NLP approach. They proposed that the NLP problem can be solved by first solving the linear model to provide initial values for the NLP optimisation.

Alva-Argáez, Kokossis and Smith (1998a, 1998b) proposed a two-phase procedure for the solution of a non-convex MINLP problem. In phase 1, a sequence of MILP sub-problems is solved by obtaining a convex projection of the non-convex feasible region. This is done by fixing the outlet concentrations from all operations. The solution to the MILP sub-problem results in an upper-bound for the MINLP. They also include a penalty term in the objective function that allows for errors in the linearised mass balances around each unit. The weighting factor of the penalty term is set higher for each iteration, thus the procedure converges to a feasible solution. This solution is then used as an initialisation point for the MINLP, which is solved in phase 2. Global optimality is not guaranteed with this method.

Galán and Grossman (1998) developed a solution technique for a non-linear, non-convex problem. They proposed a search procedure which involves the sequential solving of a relaxed linear model (MILP) and a non-linear model (MINLP). This method yields global or near-global optimum solutions.

4.4.3.1 Solving procedures

Buehner and Rossiter (1996) recommend the following steps to be followed in a numerical approach to reducing emissions:

- List emission sources, rates and applicable pollution prevention and control options.
- Establish the applicability and cost relationships for each of the control technologies.
- Determine compatibility of each technology to each of the others.
- Calculate the maximum reduction in emissions achievable with each technology, and calculate the corresponding total annualised cost.
- Establish which technology combination provides the least cost solution for any given reduction in emission.
- Plot the results in terms of minimum cost versus emission rate.

The results from the plot can then be used to find an optimum point where the total cost per emission reduction is at a minimum. These plots allow industry and regulators to explore the impact of process changes on cost and emission levels, and to define the most effective means of achieving an emission target.

4.5 Application of pinch analysis in the pulp and paper industry

The pulp and paper industry is one of few water-based industries, and the only industry where the final product consists of about 10% water (Koufos and Retsina, 2001). New environmental regulations must be met within a climate of intense competition. Therefore, ignoring novel technologies and continuing to do things in the old way could lead to being non-competitive (Koufos and Retsina, 2001).

Plant wide energy or water pinch is a practical tool for energy and water management in a mill (Koufos and Retsina, 2001). The benefits of pinch analysis are:

- Meaningful energy/water targets.
- Feasible projects with real savings.
- Essential insights into energy/water flows, distributions, benchmarks and scope.

Koufos and Retsina (2001) state that using a graphical approach for multi-contaminant pinch analysis is not practical, and therefore recommend using mathematical programming techniques to optimise the system cost and account for all contaminants.

Bédard, Sorin and Leroy (2001) list the following steps to be followed when doing a pinch analysis for a mill

- Data gathering and formulation of mass and energy balances by means of a simulation package.
- Identification of the main contaminants and their maximum allowable concentration in the water streams, as well as other process constraints.
- Apply pinch analysis using software to determine the minimum freshwater target and design to achieve the target.
- Verify the re-use scenarios proposed by the software by incorporating them into the mill simulation.
- Conduct an economic analysis and select scenarios that are within the mill's acceptable payback period.

Koufos and Retsina (2001) added a step to the process where the design is reviewed and new constraints imposed. They also include the possibility of including regeneration options into the scheme to lower the targets. Koufos and Retsina (1999 and 2001) followed a mathematical programming approach, where the operating and capital costs are included in the targeting stage. This means that an economical analysis of every design is already included in the resulting design.

Savulescu, Hammache and Bédard (2001) followed the same approach to performing a pinch analysis as outlined by Bédard, Sorin and Leroy (2001) and Koufos and Retsina (2001). They used the simulation package WinGEMS to obtain the mass/energy balance for the mill. They then used the simulation model to evaluate the impact of the proposed water and energy savings projects on the mill operation.

4.5.1 Savings reported

Wising, Berntsson and Stuart (2005) report that an energy pinch analysis at a Kraft pulp mill lead to steam demand savings of 4.0 GJ/t, and excess heat can be used for evaporation. This is done by removing all pinch violations in the system.

Koufos and Retsina (2001) report the following steam savings obtained from energy pinch studies performed by them.

Table 4-1 Practical steam savings identified by pinch analysis

Mill type	US$/ston product
Bleached Kraft/NSSC	2.61
Bleached Kraft/TMP and Other	4.50
Bleached Market Pulp	4.95
Non-integrated Papermaking	1.17
Kraft/NSSC/OCC	2.61
Sulphite or Semi-sulphite	3.96

Bédard, Sorin and Leroy (2001) report the following savings identified for a paperboard mill through following the process integration technique:

- 80% reduction in freshwater consumption.
- 50% reduction in process water volume to be treated.
- 40% reduction in the capital cost of a new evaporation unit. and 50% reduction in operating cost of evaporation unit.
- 3 ton/day increase in production through fibre recovery.

4.6 Conclusions on pinch analysis literature review

A large amount of development has been done in the areas of pinch analysis. The earlier graphical targeting methods give a conceptual insight into the problem and point to possible designs. However, when extra components are added to the problem and costs have to be optimised, these problems become too complex for these graphical targeting procedures.

The trend seems to be towards using numerical methods such as mathematical programming procedures to solve more complex problems. Mathematical programming is not without difficulty, as non-linear problems are often non-convex, meaning that global optima are often not found. A large amount of research has gone into this area in recent years.

The *WaterPinch*™ software, as used in this dissertation, is based on mathematical programming techniques, but also provides graphical insights, which makes the solution easier to understand.

Chapter 5 Methodology

5.1 Pinch analysis strategy followed

The objectives of this pinch analysis are:

- To find an effluent treatment solution that is more cost effective than end-of-pipe treatment. As pinch analysis provides an optimum solution, this solution may be cheaper and more beneficial to the river than end-of pipe treatment, which is traditionally an expensive option.

- To ascertain whether there are effluent treatment, recycling and discharge scenarios that could be beneficial to both the mill and the river. This involves looking at the balance and interactions between load and volume to the river and cost to the mill.

- To evaluate water pinch analysis as a transparent tool for the regulator and industry to find solutions that will benefit the environment without the industry being penalised unnecessarily. Optimum-cost profiles can potentially guide the regulation authority on how to best structure discharge limits so as to encourage industry to improve its effluent quality.

- To demonstrate the usefulness of pinch analysis to do basic risk analysis. This will be illustrated by using water pinch analysis to examine the effects of possible effluent discharge tariffs on the ultimate treatment solution. The effect of load based versus concentration based discharge limit also demonstrates this point.

- It will be shown that, for Tugela mill, a load based discharge licence will not only be less expensive than a concentration based limit. but that the river will also benefit from a load based limit.

5.1.1 Finding an optimum-cost profile

The most obvious use of a process optimisation technique such as water pinch analysis is to find the optimum solution to a treatment network design problem. This means that the lowest global treatment cost would be found, with one resulting network design at one effluent discharge volume. This approach is sufficient when all variables such as discharge limits and discharge tariffs are known, as it enables the user to find the lowest cost treatment network that will achieve these limits.

However, in the negotiation process between the factory and the regulatory authority, neither party has jurisdiction over the entire system that has to be optimised, which, in this case. comprises the operation of the mill and the state of the river. Furthermore the frameworks for evaluating the two parts of the system are different, and not easily reconciled. Ideally the negotiation should be supported by some form of data which allows both parties to evaluate the effect of any decision on the part of the system which is their own responsibility, without making any assumptions about the value system that each will use in their evaluation.

Thus, in order to provide a deeper understanding of the effect of various unknown elements, it will be beneficial to use water pinch analysis to obtain an optimal-cost profile by varying certain elements such as effluent flow. concentration and discharge cost. and calculating an optimal point for each of these variations (that is, optimal from the mill's point of view). By fixing the effluent discharge volume and its corresponding load or concentration limits. the optimised water treatment network and cost can be obtained for that specific discharge volume. By finding an optimum solution for each discharge volume, an optimum-cost profile as a function of discharge volume is obtained. The optimum-cost profile can also be expressed in terms of contaminant load discharged to the river. These optimum-cost profiles provide an objective picture of the effect of potential effluent regulation decisions on both the mill and the river, without making any assumptions about how the impact on the river will be assessed by the regulator.

As all optimum-cost profiles are obtained using the same water pinch optimisation model, various scenarios can be compared objectively on a cost, volume and river load basis.

5.1.2 Finding a river-load profile

In addition to obtaining an optimum-cost profile, the contaminant load on the river as a function of effluent discharge can also be obtained from the optimisation model results. This can be defined as the river-load profile. By studying the river-load profile in conjunction with the optimum-cost profile, an option can be selected that is both beneficial to the mill and the river.

5.1.3 Profiles analysed

There are two main factors that influence the outcome of the pinch analysis results. They are:

- the effluent discharge specification – load vs. concentration
- the possibility of future effluent discharge tariffs

These factors should be considered in combination to obtain optimum-cost and river-load profiles for all scenarios.

5.1.3.1 Load based discharge limits

Assuming that a load based effluent limit is imposed, the mill has to consider the possibility of effluent discharge tariffs being implemented in future. An analysis has to be done for a load based limit, with or without effluent discharge tariffs, and optimum-cost and river-load profiles have to be obtained for each of these scenarios.

5.1.3.1.1 Without discharge tariffs

In this scenario, no effluent discharge tariffs are imposed, and the contaminant discharge limits are set in terms of contaminant load to effluent instead of concentration only. This allows the concentration to rise proportionally as the effluent discharge volume decreases.

5.1.3.1.2 With discharge tariffs

The same as the previous scenario, but effluent discharge tariffs are imposed. This means that there may be a driving force to reduce effluent volume, as the balance between effluent discharge cost and treatment costs changes.

5.1.3.2 Concentration based discharge limits

Assuming that a concentration based effluent limit is imposed, the mill has to consider the possibility of effluent discharge tariffs being implemented in future. An analysis has to be done for a concentration based limit, with or without effluent discharge tariffs, and optimum-cost and river-load profiles have to be obtained for each of these scenarios.

5.1.3.2.1 Without discharge tariffs

This refers to a scenario where no effluent discharge tariffs are imposed, and that specific concentration limits are set for each contaminant. This means that, as effluent volume is reduced, and the concentration increases, the concentration limit is soon reached, and no more recycling can be done without tertiary treatment of effluent to reduce contaminant concentrations. The cost rises as more effluent is recycled.

5.1.3.2.2 With discharge tariffs

As above, but in this scenario effluent discharge tariffs are imposed. The need to further recycle effluent now depends on the balance between the treatment costs and the discharge costs.

5.2 Tools used for pinch analysis

A water pinch analysis requires a mass and contaminant balance for the system being investigated. This mass balance data is then used to set up a water pinch optimisation model. The optimisation model incorporates flow and contaminant constraints, treatment unit specifications, as well as capital and operating cost data. All of these parameters are set by the user. The model can then be optimised to find the minimum cost to achieve a distributed effluent treatment solution within the bounds of the model.

For this project, the optimisation model was used to find a minimum cost for various different effluent flow and contaminant specifications. This way, an optimum cost profile is obtained, which gives a more complete picture than merely finding one global optimum solution.

The tools used to set up the mass balance and optimisation model are discussed below.

5.2.1 Mass balance – *WinGEMS*™

In order to complete a pinch analysis, it is important to have a mass balance of the whole process. There are several ways of doing this, such as using a spreadsheet or a commercial program. The program used in this case is *WinGEMS*™. *WinGEMS*™ is a simulation software package, developed for the pulp and paper industry. The package allows detailed mass balances to be done with relative ease.

'GEMS (General Energy and Material balance System) is a modular program designed to perform mass and energy balance calculations. Calculations are grouped together in modules called blocks. The program has a wide selection of blocks that perform process calculations specifically for the simulation of pulp and paper systems.

The modular concept that *WinGEMS*™ uses makes it possible to simulate many different processes using a finite number of calculation blocks. A *WinGEMS*™ simulation project is created by diagramming a process using GEMS blocks and streams. The program then calculates the blocks iteratively to converge on a solution.

Appendix A contains a detailed description of the *WinGEMS*™ mill mass balance used to generate the necessary input data for *WaterPinch*™, the commercial pinch software package. The simulation was set up as a prior exercise and verified by extensive flow and contaminant monitoring programme.

5.2.2 Pinch analysis optimisation model - *WaterPinch*™

WaterPinch™ is the software package that was used to set up the optimisation model. To develop a water pinch model that accurately represents the process, the water-using system has to be specified in terms of various *nodes* that represent the water use in the actual plant. The nodes which make up the water-using system are classified as follows:

- *Sources* are nodes that have a supply of water. Sources that have a fixed flowrate are called *process sources*. Sources that have variable flow rates are called *utility sources*.

- *Sinks* are nodes that have a demand for water. Sinks that have fixed demands are called *process sinks*. Sinks that have variable demands are called *utility sinks*.

- Nodes that have both an inlet and an outlet are termed *unit operations*.

  - *Process unit operations* are typically operations that have fixed water demands and supplies. Operations within a process unit operation typically add contaminant mass to the water stream via mass transfer from a process stream. Process unit operations have fixed inlet and outlet flow rates; however, it is not necessary to maintain a mass balance around a process unit operation. A maximum of five inlets and outlets may be specified for an individual process unit operation. Maximum allowable inlet concentration limits may be set for each sink.

  - *Utility unit operations* are typically operations that treat or regenerate wastewater arising from the process unit operations. Operations within the utility unit operation remove contaminant mass from the water streams. Utility unit operations always have one sink and either one or two sources. Utility unit operations have a variable inlet flow rate, which is split into a maximum of two dependent outlet flows. A flow and mass balance is required around a utility unit operation. The inlet flowrate may be constrained between minimum and maximum limits, and a maximum concentration limit for the inlet may be set.

5.2.2.1 Mass transfer relationships

The mass transfer relationships between the sources and sinks of both process unit operations and utility unit operations need to be mathematically represented in the model. This model can then be optimised using the *WaterPinch*™ software. Mass transfer relationships can be represented as one of the following:

- Fixed outlet concentration – the outlet concentration will be fixed at the value specified and will have no relationship to any inlet concentration.

- Outlet concentration equal to inlet concentration – The outlet concentration will always be the same as the inlet concentration. This type of relationship can be used if a contaminant simply passes through a unit operation.

- Factor increase – The outlet concentration will be proportional to the inlet concentration.

- Constant addition - The outlet concentration will be equal to the inlet concentration plus a constant. The concentration therefore increases by a constant amount, regardless of inlet concentration.

- Mass pick-up – A constant mass load of contaminant will be transferred to the water in the unit operation.

- General Equation – Any of the above relationships can be modelled with this equation

The *WaterPinch*™ software also provides a number of standard utility unit operations to represent some commonly used treatment units. The general equations and relationships between the inlet and outlet streams are automatically set up in these standard unit operations. These unit operations include the following: generic treatment unit, reverse osmosis, backwash filter, precipitator, dissolved air flotation, air stripper, steam stripper and ion exchange. Alternatively, a generic utility unit operation is available where the user can specify the relationship between the inlet and outlet streams.

5.2.2.2 Costs

Two basic cost types may be specified in *WaterPinch*™. They are *fixed hourly costs*, and *variable operating costs*.

- *Fixed costs* are one-off costs that are incurred when a decision is made that has a related fixed cost. Fixed costs are converted to a time-dependent basis by means of a predetermined annualisation factor.

- *Variable costs* are dependent on water or contaminant mass flowrate. Usually, freshwater sources, effluent sinks and utility unit operations have variable costs associated with the amount of water extracted, discharged and treated.

5.2.2.3 Optimisation

The optimisation model determines the design of the network that satisfies the specified constraints at the minimum cost whilst still obeying all other structural constraints, or bounds, set in the project. This minimum design cost, called the objective cost, is the time-dependent cost of operating the network.

5.3 Setting up the pinch analysis optimisation model in *WaterPinch*™

In order to transfer the *WinGEMS*™ model data to into the *WaterPinch*™ optimisation model, there are several steps to be followed. These involve setting of sources, sinks and contaminants, finding mass transfer relationships, setting bounds and defining existing and generic treatment units.

5.3.1 Selecting contaminants

Although there are several important contaminants that could be considered for the study, it was decided to only use the most important contaminants in terms of effluent limits. The contaminants are sodium, dissolved wood solids (DWS), suspended solids (SS) and ash.

Additional components, such as temperature and colour are outside the scope of this investigation, and were not considered mathematically. However, in setting recycling bounds in the optimisation model in *WaterPinch*™, these factors were indirectly considered.

When recycling effluent to reduce effluent volume, energy is saved by virtue of the fact that less heat is purged from the mill via the effluent. Analogous to the cycling up of dissolved contaminant concentration with reduced effluent volume, it follows that temperature in the mill circuits may increase in a similar way. This energy saving may be beneficial, especially in the paper machines where higher temperatures are generally desirable. However, these high temperatures may be detrimental to a biological treatment system, and may therefore have to be pre-cooled before treatment.

The effects of these components have to be considered before any final designs are done. For this investigation, it is assumed that the bounds set will prevent any unwanted recycles.

5.3.1.1 Sodium

Sodium is the most important inorganic component in the effluent stream. This is because the pulping chemicals used in the process are sodium based, and although a large proportion of the sodium is recovered and converted back to caustic soda, there is a significant soda loss carried forward with the pulp and transferred into the effluent.

The mill is currently close to the concentration limit specified for sodium, and therefore it is of concern for effluent treatment and discharge investigations.

It has to be noted that sodium is not a contaminant in all instances. If the sodium is redirected into the correct loop within the mill, it becomes a desirable component. This could potentially create a sink for sodium within the process itself.

Sodium is not removed through conventional separation and biological treatment units. Desalination or evaporation is required to reduce sodium levels in the effluent. However, these processes also create a concentrated brine stream that has to be disposed of. Sodium removal is therefore relatively expensive compared to COD and TSS removal.

5.3.1.2 Dissolved wood solids

Dissolved wood solids (DWS) is the sum of all dissolved organics in any process stream. It originates mainly in the digesters and the delignification step, as the lignin in the wood is dissolved. Most of this dissolved lignin is washed out of the pulp and taken to recovery, but some is carried forward with the pulp and transferred to the effluent. The dissolved wood solids is a measure of the chemical oxygen demand (COD) in the effluent, and is taken as half of the COD concentration.

The mill will be forced to reduce the COD concentration in the effluent substantially, and this can be done through biological treatment of the effluent streams.

5.3.1.3 Suspended solids and ash

For the purposes of this exercise, suspended solids (SS) is defined as all suspended material in the water, excluding ash, which is accounted for separately. This is done because streams high in fibrous suspended solids may be allowed to enter processes that do not allow any ash particles to be present. Therefore, distinction is made between different grades of suspended material.

Ash enters the effluent system via the boilers blow-down, which is high in suspended ash. Currently, the ash enters the effluent clarifier with the fibrous suspended solids and is removed and disposed. However, when investigating recycling opportunities, it is important to be aware of the ash content in each process stream.

5.3.2 Selecting sources and sinks

The first step in transferring *WinGEMS*™ information to the optimisation model in *WaterPinch*™ is to decide which streams should be defined as sources and sinks. Not all process streams are sources or sinks, as not all process streams participate in mass transfer processes. However, in a pulp and paper mill, water is an integral part of the process, and is therefore impossible to exclude from the calculations.

5.3.2.1 Process sources and sinks

With process sinks and sources, the flow to and from the sink/source is set and cannot be changed. The contaminant concentrations are allowed to vary within the limits set by the user for the sink/source. The model is required to mix various streams to obtain the sink volume flow, within the concentration limits.

A process source is a function of a particular sink of the same process unit operation. The process source quality will be calculated using the sink quality. These relationships are set when building the optimisation model.

Figure G-1 in Appendix G shows a mill layout diagram with all the sources and sinks selected for this study. As can be seen from the drawing, the main pulp streams from the pulp transfer to the paper machines are included as sinks for the paper machines and sources for pulp transfer. This was done because, although the pulp streams may not be re-routed by the model for use in other processes, the pulp streams carry large amounts of water and contaminants, which eventually become part of, and therefore affect, process source quality in the paper machines and pulp transfer section. Figure 5-1 shows the effect of pulp being transferred on the water circuits in the pulp transfer section and paper machines.

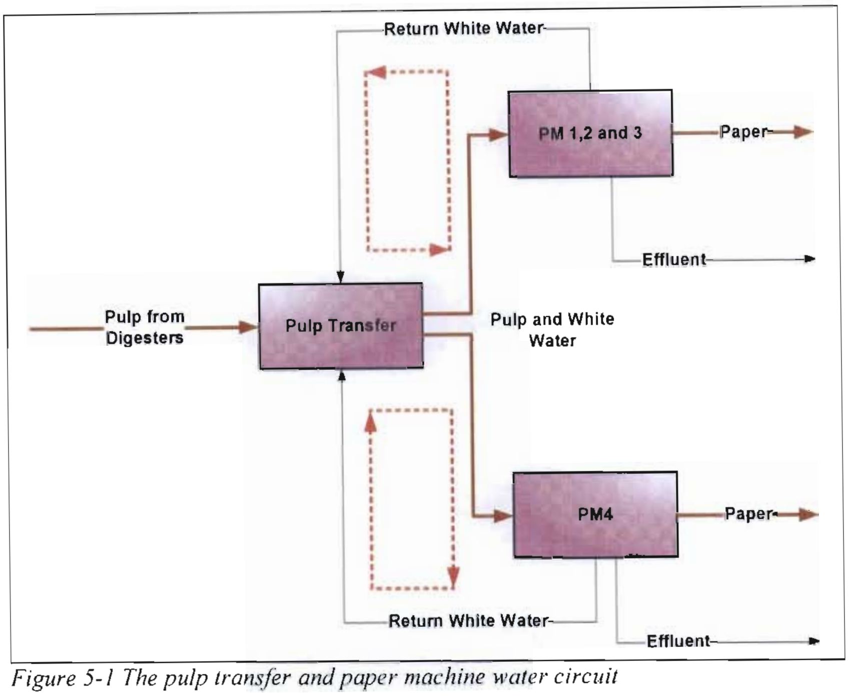


Figure 5-1 The pulp transfer and paper machine water circuit

Process source and sink flow rates are set for all scenarios and can not be changed. The only change that can take place is the number and combination of process or utility source streams that are mixed to make up a process sink.

For certain units, the input streams are mixed before entering the process sink. This is done where groups of streams are bundled together to form one sink. The mass transfer relationships were then derived for this combined sink, instead of each separate stream.

This method evolved when it was found that the source quality could not be attributed to the effect of one single sink, but is affected by a combination of feed streams. These streams were therefore combined into a single sink. in order to find a mass transfer relationship that defines the source.

Figure 5-2 illustrates the use of a combined sink to replace several individual sinks

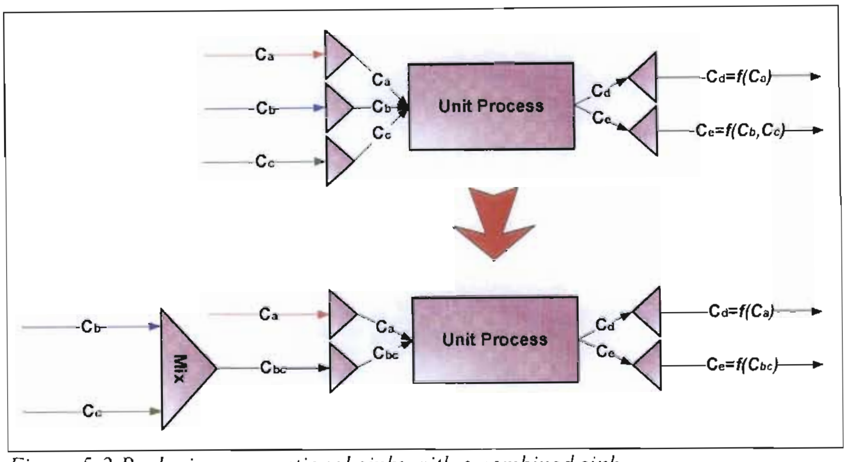


Figure 5-2 Replacing conventional sinks with a combined sink

This technique was used for the paper machines, pulp transfer and boilers sections.

Table C-1and Table C-2 in Appendix A contain a list of all process sinks and sources for the project.

5.3.2.2 Utility sources and sinks

Utility sources and sinks are sources/sinks where the flow rate is allowed to change, as required. These sources/sinks are associated with utility unit operations, such as treatment units, and are also used to define mill water supply sources and effluent discharge sinks.

By definition, in the *WaterPinch*™ optimisation model, all utility or process sources have to report to either a process sink or a utility sink. Each sink has an associated cost and contaminant concentration or load limit attached to it. Some utility sinks may also have a maximum allowable flow rate defined.

In addition to the normal water sources and effluent sinks, additional brine, ash and waste sinks have been defined. The model may use these sinks as required. A special utility sink was also created where a small stream could be recycled back to the recovery circuit, under special circumstances (see section 5.3.5.6).

Figure G-1in Appendix G shows the utility sources and sinks for the base case simulation. Other utility sources and sinks can be added as required, as simulation bounds change. Utility sources and sinks are also added when generic treatment units are added by *WaterPinch*™. Table C-3 and Table C-4 in Appendix C contain a list of all utility sinks and sources for the project.

5.3.3 Finding mass transfer relationships and setting up equations

After selecting the sources and sinks for the project, the mass transfer relationships between the sources and sinks had to be calculated. These relationships were obtained from the *WinGEMS*™ model. A concentration change was made in the sink concentration of a process unit operation, using *WinGEMS*™, and the effect on the corresponding source was then measured. This way, a linear correlation was obtained that defines the output source concentration as a function of input sink concentration. This procedure was followed for all sources on all process unit operations.

In cases where the source concentration is a function of several input streams, the input streams were combined to form a single sink. The linear equations were then derived from this combined sink. (see section 5.3.2.1).

The equations used for sodium and DWS is of the following format:

$$C_{out} = C_{in}.A + B$$

Where,
C_{out} = outlet concentration (of the source)
C_{in} = inlet concentration (of the sink)
A,B = linear equation coefficients

By specifying the constants A and B, obtained from the *WinGEMS*™ model, the user gives the optimisation model the required information to calculate source conditions for any given sink conditions. It is assumed that the linear equations derived from *WinGEMS*™ are valid across the allowed concentration range for each sink/source combination.

Appendix F contains the linear equations, derived for DWS and sodium, from the *WinGEMS*™ model for each process source.

In most cases, the TSS and ash concentrations of source streams are not allowed to vary, as the input TSS and ash of the input streams are set. The pulp consistencies (concentrations) of these sinks and sources are set at a constant concentration, as it is a process related figure and is not allowed to be changed by the optimisation model.

In cases where the input TSS or ash concentrations are allowed to change, the mass pick-up equation was used instead of the concentration equation. The equation is:

$$C_{out} = \frac{F_{in}.C_{in} + A}{F_{out}}$$

Where,

C_{out} = outlet concentration (of the source)

C_{in} = inlet concentration (of the sink)

F_{out} = outlet flow (of the source)

F_{in} = inlet flow (of the sink)

A = mass pickup, Δm

This equation was used because it was assumed that the mass pickup from sink to source is a constant tonnage, independent of the concentration of the sink. It is assumed that the derived equations are valid across the allowed TSS and ash concentration range for each sink/source combination.

Appendix F contains the equations for TSS and ash, derived from the *WinGEMS*™ model for each process source.

5.3.4 Setting bounds for the project

In order to get reliable results from the optimisation model, it is necessary to set realistic and reasonable bounds for the model to operate within. This ensures that all matches made are realistic and within the operating limits and specifications of the mill. A match between a source and a sink is made when one or more process or utility source streams, or part thereof, are mixed to form the feed to a process or utility sink. The mixed stream has to conform to the flow and concentration limits set for the destination sink.

These bounds should include the maximum allowable concentration limits for each sink, as well as forbidden and compulsory matches. A limit on the maximum number of streams allowed to be mixed to make up a sink can also be set for each sink.

5.3.4.1 Setting forbidden matches

There are many matches that are not allowed in the optimisation model, for practical considerations.

- No reverse osmosis (RO) or brine concentrator brine, or other solid waste from utility unit processes are allowed into any process sink, even in small quantities, unless specified.

- No direct recycle around a process unit is allowed. For purposes of this exercise, it is assumed that no further internal effluent recycling options are possible, and that the internal processes are optimised in terms of water use. Therefore, it can be assumed that the effluent source produced by a process is already minimised, and cannot be re-used within that same process.

- No process source can be directly recycled to a process sink, unless expressly specified. Therefore, process sources have to go through some form of treatment unit, and become a utility source, before being recycled to a process sink.

- No mill water or domestic water is allowed to go directly to a utility sink. This means that effluent may never be diluted using a clean water source. The only exception to this rule is that cooling water that is currently going to effluent may still go to effluent.

Table D-1 in Appendix D contains all flow bounds set for the project.

5.3.4.2 Setting compulsory matches

In certain instances, it is necessary to force the optimisation model to maintain certain matches. This is done for practical reasons, or to maintain current operation in areas where changes are not desired. Table 5-1 shows the compulsory matches within the project.

Table 5-1 Compulsory matches for the project

From source	To sink	Volume (t/h)
Kraft Recovery out 1	NSSC pulping in 1	24
Kraft Recovery out 1	Boilers in 1	17
Pulp transfer out 3	Paper machines in 2	78
Pulp transfer out 3	Wasteplant in 2	162
Pulp transfer out 4	Paper machine in 5	839
Clarifier 1 out 2	Wasteplant in 3	42
Paper machines out 1	Pulp transfer in 2	649
Pm4 out 2	Pulp transfer in 2	240
Pulp transfer out 4	PM4 in 4	209
Vortex de-gritter filtrate	Boilers in 1	79
Boilers out 2	Vortex de-gritter inlet	263

The matches shown in Table 5-1 are set out below:

- The main compulsory matches set within the project are the pulp flows from the pulp transfer section to the paper machines. Although the pulp streams are included in the project, as described in section 5.3.2, these streams are not allowed to be used anywhere but as feed to the paper machines. Therefore, these streams are set as compulsory matches in the optimisation model.

- The paper machine clarifier underflow is currently returned to the waste plant for fibre recovery. This practice will continue in future, and is therefore set as a compulsory match.

- The paper machine backwater currently being returned to the pulp transfer section is forced to also be returned in future scenarios. It is normal paper machine operation to transfer pulp with paper machine backwater, and therefore the return of these streams to pulp transfer is set as a compulsory match.

- In future, the vortex de-gritter will be used to remove larger ash particles from the boilers effluent. A portion of the vortex de-gritter filtrate will be returned to the boilers as quench water. This return stream is set as a compulsory match, as one of the main purposes of the vortex de-gritter is to remove ash from the boilers effluent in order to recycle effluent at source, to replace mill water. Therefore, the unit is forced to accept a certain amount of boilers effluent, and send a certain amount of filtrate back to the boilers.

- The evaporator condensate going to the boilers for ash quenching was set as a compulsory match.

- The evaporator condensate used for NSSC brown stock washing was set as a compulsory match.

- In cases where mixing units were used to mix process sinks before entering a block (as discussed in 5.3.2), the flows from the mixing units to the corresponding process sinks were set as compulsory matches.

Table D-1 in Appendix D contains all flow bounds set for the project, including compulsory matches. From Table D-1 it is clear that recycling from process sources to process sinks is generally forbidden. Practical considerations were used to set all bounds. Of the 1936 possible matches, 256 matches are allowed. Many of the matches that are forbidden would have been infeasible anyway in the optimisation model, due to the concentration limits imposed, but were set to zero to improve the calculation speed of *WaterPinch*™.

5.3.4.3 Setting minimum flow required for recycle (Ztol)

Theoretically, the model may mix as many streams as it requires to obtain a sink feed stream of the correct quality and flow. This often involves mixing a large quantity of a cleaner stream with a small quantity of a smaller stream to obtain a sink feed stream that is as close as possible to the upper concentration limit of the sink. Although. mathematically. this may be the optimal way to mix the streams, practically it would involve piping various small streams to one point, or having one large pipe and one or two very small pipes running to a certain application point. The resulting piping layout would not only be impractical to build. but also very costly.

One way of working around this problem in *WaterPinch*™, is to give the model actual geographical locations of processes and piping costs, which will form part of the objective cost function. which is minimised. However, for this exercise. geographical positions and piping cost have not been included.

Instead, it was decided to set a minimum flow (Ztol) limit on the process sinks in the *WaterPinch*™ model. By setting the Ztol flow for the sink, the optimisation model does not allow any source stream to be used as part of a sink feed, unless it can be used at or above the amount specified by the user. Where necessary. the Ztol limit for a sink was specified so that very small amounts of clean or dirty source water were not allowed into the sink. This means that the number of feeds to the sink is in effect limited. Also, very small amounts of any stream entering a sink are not allowed. If a potential feed stream can not be used up to the Ztol quantity, due to concentration limitations, then the match of that stream to the sink becomes a forbidden match.

Table D-2 in Appendix D contains a table of Ztol bounds set for the project.

5.3.4.4 Specifying contaminant limits for recycling

The optimisation model requires the setting of contaminant concentration limits for each sink. If no special limits are set for a sink, the original concentration of the sink is used as an upper concentration limit. The most conservative approach is to use original concentration values as maximum concentration limits. This ensures that every sink receives the same quality water as it does presently. However, such limits severely inhibit the recycling opportunities within the mill.

For this project, the concentration limits were relaxed, where possible, whilst still ensuring that the process could handle the specified water qualities. Table 5-2 contains a list of all process sinks in the project with original and adjusted contaminant limits.

Table 5-2 Process sink contaminant concentration limits

Sink name	Flow (m³/h)	Basecase concentration				New maximum limits			
		Na	DWS	SS	Ash	Na	DWS	SS	Ash
		ppm				ppm			
Woodyard in	14	41	25	10	0	∞	∞	50	0
Kraft recovery in 1	76	41	25	10	0	41	25	10	0
Kraft recovery in 2	0.22	600	60	0	0	600	60	0	0
Kraft recovery in 3	49	41	25	10	0	∞	∞	50	0
Kraft pulping in 1	222	65	572	0	0	65	572	9	0
Kraft pulping in 2	42	41	25	10	0	41	25	10	0
Kraft pulping in 3	59	41	25	10	0	41	25	10	0
NSSC pulping in 1	24	65	572	0	0	65	572	9	0
NSSC pulping in 2	108	41	25	10	0	41	25	10	0
NSSC pulping in 3	54	41	25	10	0	41	25	10	0
NSSC pulping in 5	21	41	25	10	0	41	25	10	0
Boilers in 1	271	43	59	7	0	∞	∞	10	59
Boilers in 3	193.6	41	25	5	0	41	25	5	0
PM4 in 3	79	41	25	5	0	41	25	5	0
PM4 in 4	393	168	309	21276	0	∞	∞	21300	0
Recovery2 in	86.4	41	25	5	0	41	25	5	0
Papermachine in 2	78	224	357	612	0	∞	∞	∞	0
Papermachine in 5	1847	184	325	18175	0	∞	∞	18200	0
Pulp transfer in 2	1064	224	357	612	0	∞	∞	∞	0
Pulp transfer in 5	9	41	25	10	0	41	25	10	0
Wasteplant in 1	83	41	25	10	0	∞	∞	10	0
Wasteplant in 2	162	279	477	612	0	∞	∞	∞	0
Wasteplant in 3	42	223	245	25000	0	∞	∞	∞	0

As can be seen from Table 5-2, the ash concentration limit is the strictest, with no ash being allowed in the paper machine circuits. In many instances where mill water or domestic water is presently used, the concentration limits could not be relaxed.

As with process sinks, contaminant limits also need to be set for utility sinks. These limits ensure that each treatment unit receives a feed quality that is within its operating range. Table C-3 in Appendix C lists all utility sink flow and concentration limits. The selection of treatment units is discussed in section 5.3.5.

5.3.5 Selection of treatment units

After selecting and defining process units, sources and sinks, it is necessary to provide the optimisation model with effluent treatment units that may be used to improve the effluent quality and hence may make it possible to recycle treated effluent back to the process.

By specifying a number of generic treatment units, the optimisation model may use any combination of these treatments to obtain an optimum treatment and recycling solution.

Each treatment unit has to be specified in terms of performance, treatment cost and capital cost. Inlet concentration or load limits may also be set to ensure that the treatment unit performs within specifications.

The treatment units were selected to cater for solids removal, COD removal and desalination of effluent. Some of the units perform only one task, whereas other units perform more than one of these tasks.

5.3.5.1 Biological effluent treatment plants

Two biological treatment units were defined for this project. Both have identical COD removal efficiencies – however, the maximum allowed SS and ash to each treatment plant are specified differently.

The reason for having two separate biological treatment plants is to allow the optimisation model to separately treat effluents of different qualities, if required. This means that, if there are two effluent streams that both need to be biologically treated, but the one stream contains ash that makes it unsuitable for recycling, this stream can be treated separately from the cleaner stream that does not contain ash. This is in line with the concept of a distributed effluent treatment system design (Wang and Smith, 1994b).

The first effluent treatment plant is designed to treat paper machine effluents that contain no ash particles, whilst the second treatment unit may treat more contaminated effluents. Both units have an upper limit for suspended solids that ensures that solids do not build up to excessive levels in the biological treatment plant.

The process used is assumed to be oxygen activated sludge treatment, and secondary clarification and return and handling of bio-sludge are included in the processes.

5.3.5.1.1 Performance specifications

Table 5-3 shows the inlet flow and concentration limits for the paper machine effluent biological treatment unit and Table 5-4 shows the performance specifications for this unit.
As can be seen from the above tables, the biological treatment units are identical, except for the maximum flow, SS and ash limits.

Table 5-3 Paper machine effluent biological treatment unit inlet limits

Utility Treatment Unit Inlet Limits	
Maximum flow (t/h)	2500
Max Na (ppm)	No limit
Max DWS (ppm)	No limit
Max SS (ppm)	220
Max Ash (ppm)	6

Table 5-4 Paper machine effluent biological treatment unit performance specifications

Utility Treatment Unit Performance Specifications	
Na removal (%)	0
DWS (COD) removal (%)	75
SS removal (%), in bio-clarifier	80
Ash removal (%), in bio-clarifier	20

Table 5-5 shows the inlet flow and concentration limits for the general effluent biological treatment unit and Table 5-6 shows the performance specifications for this unit.

Table 5-5 General effluent biological treatment unit inlet limits

Utility Treatment Unit Inlet Limits	
Maximum flow (t/h)	2000
Max Na (ppm)	No limit
Max DWS (ppm)	No limit
Max SS (ppm)	200
Max Ash (ppm)	40

Table 5-6 General effluent biological treatment unit performance specifications

Utility Treatment Unit Performance Specifications	
Na removal (%)	0
DWS (COD) removal (%)	75
SS removal (%), in bio-clarifier	80
Ash removal (%), in bio-clarifier	20

5.3.5.1.2 Forbidden and compulsory matches

Both effluent treatment plants are restricted by relatively low allowable SS and ash in the feed. This forces optimisation model to pre-treat the majority of the feed to the biological treatment plants in the DAF or the clarifier to remove solids.

No direct recycle around the biological treatment plant is allowed, and no utility water is allowed to enter the treatment plant directly. In reality, the biologically treated effluent contains no more biodegradable COD and would pass through the biological treatment plant unchanged the second time. Therefore, biologically treated effluent may not be re-fed to the DAF or the clarifier, as allowing this could cause the optimisation model to treat the same water over and over until no COD remains. If this limit was not set, the model would use the less expensive DAF unit to remove the bulk of the COD, and use the more expensive biological treatment plant only as a polishing step, which is clearly not practically possible.

5.3.5.2 Clarifiers

The mill currently uses two clarifiers to treat effluent. However, the paper machine effluent clarifier (Clarifier 1) is undersized and can not handle the full paper machine effluent from the mill. This results in Clarifier 1 being bypassed to the general effluent clarifier (Clarifier 2). In order to avoid this, Clarifier 1 is defined as a new clarifier with a higher capacity. It is assumed that Clarifier 1 capacity will be increased before any other equipment is installed. This will also apply to the conventional treatment option. Therefore, no capital costs were included for Clarifier 1 re-build.

Due to space constraints in the mill, the activated sludge plant/s will be retrofitted in the current Clarifier 2 basin. Therefore, Clarifier 2 does not exist in any future scenarios. Instead, a Dissolved Air Flotation (DAF) unit is provided for solids removal of the non-paper machine effluents.

5.3.5.2.1 Performance specifications

Table 5-7 shows the inlet flow and concentration limits for the clarifier treatment unit and Table 5-8 shows the performance specifications for this unit.

It can be seen that a 20% COD removal is observed in the clarifier. This reduction is currently observed in both clarifiers and is therefore included in the optimisation model. The outlet SS concentration for the overflow and underflow is set at a constant, as the clarifier performance will not necessarily improve if the inlet concentration is lowered. The fixed concentration encourages the optimisation model to utilise the Clarifier for its intended purpose of solids removal, and not as a COD removal or low-solids polishing step.

Table 5-7 Clarifier treatment unit inlet limits

Utility Treatment Unit Inlet Limits	
Maximum flow (t/h)	1858
Max Na (ppm)	No limit
Max DWS (ppm)	No limit
Max SS (ppm)	1200
Max Ash (ppm)	0

Table 5-8 Clarifier treatment unit performance specifications

Utility Treatment Unit Performance Specifications	
DWS (COD) removal in clarifier (%)	20
Na removal in clarifier (%)	0
SS in overflow (ppm), for all feed SS	86
SS in underflow (ppm), for all feed SS	25000

5.3.5.2.2 Forbidden and compulsory matches

Only paper machine effluents are allowed as feed to Clarifier 1. The clarifier overflow is not restricted, and may be used as and where required. The clarifier underflow is sent to the de-watering press for de-watering. However, a portion of the underflow is sent back to the waste plant for fibre recovery.

No direct recycle around the clarifier is allowed, and no utility water is allowed to enter the clarifier directly.

5.3.5.3 Dissolved air flotation (DAF)

The Dissolved Air Flotation (DAF) treatment unit is used to remove solids and COD from the effluent. The lignin is precipitated through acidification, and solids separation takes place through flotation with dissolved air.

Although the DAF unit is designed for solids and colour removal, an upper limit is set on the allowable SS and ash entering the unit, to protect it from being overloaded.

5.3.5.3.1 Performance specifications

Table 5-9 shows the inlet flow and concentration limits for the Dissolved Air Flotation treatment unit and Table 5-10 shows the performance specifications for this unit.

Apart from the solids and colour removal, the DAF unit also achieves a 30% COD removal. This value was observed in pilot plant trials done at the mill. The removal of COD is as a result of coagulation and flocculation of organic compounds in the feed stream, which is then removed in the DAF solid phase.

Table 5-9 Dissolved Air Flotation treatment unit inlet limits

Utility Treatment Unit Inlet Limits	
Maximum flow (t/h)	800
Max Na (ppm)	No limit
Max DWS (ppm)	No limit
Max SS (ppm)	1400
Max Ash (ppm)	200

Table 5-10 Dissolved Air Flotation treatment unit performance specifications

Utility Treatment Unit Performance Specifications	
Na removal (%)	0
DWS (COD) removal (%)	30
SS removal (%)	85
Ash removal (%)	85

5.3.5.3.2 Forbidden and compulsory matches

Apart from the solids concentration limits on the DAF feed, the unit is very robust and can handle any effluent. DAF sludge is sent to the de-watering press with the other solid waste streams.

No direct recycle around the DAF is allowed, and no utility water is allowed to enter the DAF directly.

5.3.5.4 Sand-filter

The sand-filter is used to filter solids from effluent. A certain percentage of the filtered water is used to backwash the sand-filter periodically. The backwash water produced by the filter has to be handled as a waste stream in the optimisation model.

As the sand-filter is designed as a polishing filter, the maximum allowable TSS to the filter is relatively low. Any higher TSS values in the feed would block the filter too quickly.

5.3.5.4.1 Performance specifications

Table 5-11 shows the inlet flow and concentration limits for the sand-filter treatment unit and Table 5-12 shows the performance specifications for this unit.

The sand-filter produces a very low-solids polished effluent that is suitable for various applications.

Table 5-11 Sand-filter treatment unit inlet limits

Utility Treatment Unit Inlet Limits	
Maximum flow (t/h)	2200
Max Na (ppm)	No limit
Max DWS (ppm)	No limit
Max SS (ppm)	35
Max Ash (ppm)	5

Table 5-12 Sand-filter treatment unit performance specifications

Utility Treatment Unit Performance Specifications	
Filtered water as backwash water (%)	5
Filtered water SS (ppm)	4
Filtered water ash (ppm)	0
DWS and Na removal (%)	0

5.3.5.4.2 Forbidden and compulsory matches

The sand-filter is only restricted by the low SS and ash limits allowed in the feed. No direct recycle around the sand-filter is allowed, and no utility water is allowed to enter the sand-filter directly.

5.3.5.5 Reverse Osmosis

Reverse osmosis is used primarily for removing salinity from the feed stream. However, solids and COD removal is also achieved by reverse osmosis. The products from reverse osmosis are ultra-pure water and a concentrated brine stream. Both of these product streams have to be considered by the optimisation model.

In order to protect the reverse osmosis unit from solids overload, the maximum allowable solids allowed into the reverse osmosis unit is set very low.

5.3.5.5.1 Performance specifications

Table 5-13 shows the inlet flow and concentration limits for the reverse osmosis treatment unit and Table 5-14 shows the performance specifications for this unit.

Although the reverse osmosis has very strict feed concentration limits, the product water from this unit is very clean and can be used in almost any application in the mill.

Table 5-13 Reverse osmosis treatment unit inlet limits

Utility Treatment Unit Inlet Limits	
Maximum flow (t/h)	590
Max Na (ppm)	No limit
Max DWS (ppm)	No limit
Max SS (ppm)	4
Max Ash (ppm)	1

Table 5-14 Reverse osmosis treatment unit performance specifications

Utility Treatment Unit Performance Specifications	
Permeate Recovery (%)	80
Na rejection (%)	96
DWS rejection (%)	100
SS and ash rejection (%)	100

5.3.5.5.2 Forbidden and compulsory matches

The feed concentration restrictions on the reverse osmosis unit are very strict. Although any stream can theoretically enter the RO, in reality only sand-filter product water is of good enough quality to become RO feed.

No direct recycle around the RO is allowed, and no utility water is allowed to enter the RO directly.

The RO brine may be sent to various utilities, and may also be used as wash water on the mud filters in the recovery section. This way, the sodium in the brine is recovered. Any excess RO brine may be dumped, at a cost, or further concentrated in a brine concentrator unit (see section 5.3.5.6).

5.3.5.6 Brine concentrator

Reverse osmosis produces a brine stream that needs to be disposed of. Often, this brine, however concentrated, is still a relatively high-volume stream, making disposal very costly. Therefore, in order to reduce the volume of the brine, a brine concentrator unit was supplied in the optimisation model. In practice, this will be an evaporative process, such as mechanical vapour re-compression. This process is expensive, as it uses steam or electricity to evaporate water from the brine.

However, concentrated brine may be returned to the recovery circuit, where the sodium is recovered in the form of caustic soda, resulting in a reduced chemical make-up cost, and also reduced effluent load.

5.3.5.6.1 Performance specifications

Table 5-15 shows the inlet flow and concentration limits for the brine concentrator treatment unit and Table 5-16 shows the performance specifications for this unit.

The brine concentrator produces a high quality condensate and a very concentrated brine stream. The condensate stream is free of ash and solids.

Table 5-15 Brine concentrator treatment unit inlet limits

Utility Treatment Unit Inlet Limits	
Maximum flow (t/h)	No limit
Max Na (ppm)	No limit
Max DWS (ppm)	No limit
Max SS (ppm)	40
Max Ash (ppm)	4

Table 5-16 Brine concentrator treatment unit performance specifications

Utility Treatment Unit Performance Specifications	
Clean condensate, % of feed	80
Na in concentrate (%)	99
DWS in concentrate (%)	99
SS and ash in concentrate (%)	100

5.3.5.6.2 Forbidden and compulsory matches

By definition, only reverse osmosis brine is allowed to enter the brine concentrator. The clean condensate may be used anywhere in the system, but may not be sent to final effluent. The brine stream may be disposed of through the brine sink provided, at a cost.

Furthermore, a portion of the brine stream may be returned directly to the recovery circuit, where the chemicals can be recovered. A special utility sink is provided for this purpose. The concentrator brine is the only stream that is allowed back to the recovery circuit via this route, as no other stream has a high enough concentration to be taken to the recovery circuit without adversely affecting the % black liquor solids.

5.3.5.7 Sludge de-watering press

A de-watering press is included in the project to handle sludge streams from the clarifier and DAF units. The sludge is de-watered to reduce the volume and hence the disposal cost. For this exercise, it is assumed that no fibre can be recovered from the de-watering press. Fibre recycling could be an option in future. but the ash-containing DAF sludge will then have to be de-watered separately.

The mill currently has a de-watering press for de-watering sludge. It is assumed that the existing de-watering press could be used as-is for future scenarios. Therefore, no capital costs were incorporated for the de-watering press.

The filtrate from the de-watering press is a stream that has to be dealt with in the optimisation model.

5.3.5.7.1 Performance specifications

Table 5-17 shows the inlet flow and concentration limits for the sludge de-watering press treatment unit and Table 5-18 shows the performance specifications for this unit.

The de-watering press de-waters the sludge, and produces a filtrate, at a constant SS and ash concentration. It is assumed that 5% of the water in the feed stream leaves with the pulp. This results in an outlet pulp consistency of approximately 16%, depending on the feed consistency.

Table 5-17 De-watering press treatment unit inlet limits

Utility Treatment Unit Inlet Limits	
Maximum flow (t/h)	No limit
Max Na (ppm)	No limit
Max DWS (ppm)	No limit
Max SS (ppm)	40000
Max Ash (ppm)	40000

Table 5-18 De-watering press treatment unit performance specifications

Utility Treatment Unit Performance Specifications	
Water out with de-watered sludge (%)	5
Filtrate SS (ppm)	400
Filtrate ash (ppm)	20
Approximate de-watered consistency (%), depending on inlet	16

5.3.5.7.2 Forbidden and compulsory matches

The clarifier underflow, DAF float and sand-filter backwash is allowed to go to the sludge press. A portion of the RO brine is also allowed to go to the sludge press, as an additional purge of brine.

The de-watered pulp is dumped via a designated solid waste sink, at a cost. The press filtrate may be sent back to the clarifier, DAF or biological treatment plant unit operations, if the quality is within the concentration limits of these units.

5.3.5.8 Vortex ash de-gritter

The boilers effluent has very high ash content. This ash would be difficult to remove in the DAF unit, and a large percentage of ash could potentially be carried through with the DAF product water if it is not removed before entering the DAF. For this reason, a vortex de-gritter is provided as a treatment unit in the *WaterPinch*™ model. The vortex de-gritter removes a portion of the ash particles in the boilers effluent. A portion of this treated effluent will be re-used ash boiler quench water, in all scenarios.

It is assumed that the vortex de-gritter will be required in all scenarios, as there will be no Clarifier 2 to remove the excess ash in future (see section 5.3.5.2). Therefore, the capital cost of the de-gritter is not included for this project, as it is assumed that the de-gritter will have to be installed before any effluent treatment option can be implemented.

5.3.5.8.1 Performance specifications

Table 5-19 shows the inlet flow and concentration limits for the sludge de-watering press treatment unit and Table 5-20 shows the performance specifications for this unit.

It is assumed that 5% of the water in the feed leaves with the ash, and that the de-gritter can reduce the ash content to 200ppm, regardless of feed ash concentration.

Table 5-19 Vortex de-gritter treatment unit inlet limits

Utility Treatment Unit Inlet Limits	
Maximum flow (t/h)	300
Max Na (ppm)	No limit
Max DWS (ppm)	No limit
Max SS (ppm)	100
Max Ash (ppm)	2000

Table 5-20 Vortex de-gritter treatment unit performance specifications

Utility Treatment Unit Performance Specifications	
Water with ash (%)	5
Na removal (%)	0
DWS removal (%)	0
SS removal (%)	0
Ash content of treated de-gritter effluent (ppm)	200

5.3.5.8.2 Forbidden and compulsory matches

The boilers effluent is forced to go to the vortex de-gritter. as this unit is provided for the express purpose of removing ash from the boilers effluent. A portion of the treated effluent will be recycled to the boilers as ash quench water.

Demineralisation plant effluent from the boilers is permitted to enter the vortex de-gritter.

5.4 Costs

The *WaterPinch*™ software allows the user to specify treatment cost as variable or fixed cost. This allows the user to specify treatment costs to be used when optimising the cost. In this project. it is important to take into account both the operational cost and the capital cost of a plant. The size of the treatment unit has a direct influence on the capital cost. and therefore this cost has to be incorporated into the calculations, in order to find the most cost-effective option.

5.4.1 Treatment unit cost calculation

For the *WaterPinch*™ optimisation model to take both capital and operational cost into account. the cost has to be linearised to obtain the variable and fixed components of the cost. as a function of treatment unit size.

5.4.1.1 Capital cost

If the capital cost for a certain treatment unit size is known, the capital cost for other size units can be extrapolated. The equation used for this calculation is (Perry, 1984):

$$Cost_{Volume_2} = Cost_{Volume_1} * \left(\frac{Volume_2}{Volume_1}\right)^n$$

Where

Cost = Capital cost at given treatment volume

Volume = Treatment volume, or size of treatment unit

n = coefficient varying between 0.5 and 0.8. A value of 0.67 was used for calculations.

When the capital cost is known for each treatment unit size is known, the annualised cost, or unacost, can be calculated for each treatment unit size. The equation used for this calculation is:

$$UnaCost = CapitalCost.\left(\frac{r.(1+r)^n}{(1+r)^n - 1}\right)$$

Where

UnaCost = annualised cost in R/y

CapitalCost = Capital cost of treatment unit in Rands

r = Rate of depreciation, % per year

n = Lifetime of plant, years

For this project, depreciation is taken at 10% per year, and the lifetime of the plant is taken as 20 years, for all treatment units.

5.4.1.2 Operational costs

If the treatment cost per unit volume is known for a treatment unit, this cost can be annualised by multiplying the cost per unit volume by the volume treated annually. Therefore, the annualised treatment cost can be obtained as a function of treatment unit size, assuming that the treatment cost per unit volume is independent of treatment unit size.

In certain treatment units, the treatment cost is not a function of volume, but a function of load treated in the treatment unit. An example of this is the biological treatment unit, where the treatment cost is a function of the DWS (COD) load removed by the unit, and is independent of the volume treated. In this case, operational cost is not annualised, but entered into the optimisation model separately as a specific cost of treatment.

5.4.1.3 Linearised cost

After annualising all relevant capital and operational costs, the sum of these costs is then plotted as a function of treatment unit size. From the plot, a linear regression is carried out to obtain a variable and fixed cost element to input into the optimisation model. Figure 5-3 shows a linearised cost curve with regression.

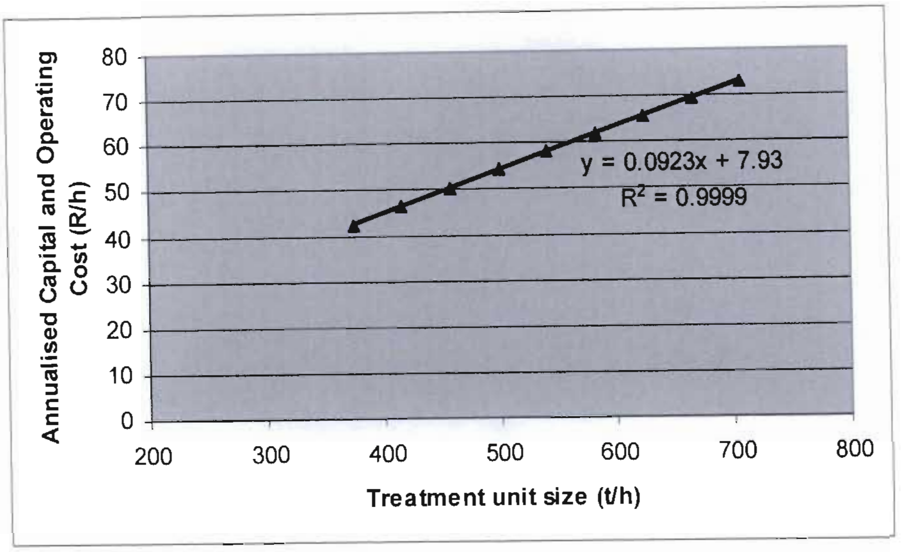


Figure 5-3 Linearised cost curve

In Figure 5-3, the slope of the line is R0.0923/t treated, and the y-intercept is R7.93/h. These two values describe the linearised cost curve for the specific treatment unit, and can be input into the *WaterPinch*™ optimisation model.

5.4.2 Capital, operating and linearised costs for selected treatment units

The technique for obtaining a linearised cost was applied to all treatment units. The linearised cost curves for each treatment unit, as well as capital and operating cost data is listed in Appendix B . Table 5-21 summarises the cost data that was used in setting up the water pinch model.

Table 5-21 Cost data for treatment units

Treatment unit	**Linearised cost curve terms**		**Other costs**
	Variable (R/t)	**Fixed (R/h)**	
Activated Sludge Plants	0.25	78.23	R0.51/kg DWS$_{entering}$
Clarifier 1	-	-	R0.08/t
Dissolved Air Flotation	0.12	15.86	-
Sand-filter	0.16	48.13	-
Reverse Osmosis	1.49	56.97	-
Brine concentrator	39.52	11.90	-
Sludge de-watering press	-	-	R0.05/t
Vortex ash de-gritter	-	-	R0.10/t

The operating cost for the biological treatment plants is expressed as cost per kg DWS entering rather than cost per volumetric loading. This is done because the biological treatment plant treatment cost is dependent on DWS loading, and not volumetric loading.

The linearised cost curve accounts for the lower capital cost of a smaller unit, forcing the optimisation model to minimise the treatment plant volume, whilst the cost per kg DWS accounts for the load on the treatment plant, irrespective of volume.

5.4.3 Other costs

5.4.3.1 Utility costs

Although water is abstracted from the river, the pumping and filtration of the mill water and domestic water results in a small cost for utility water. This utility cost is included in the optimisation model. Table 5-22 lists the utility sources and cost associated with each.

Table 5-22 Utility source costs

Utility Source	Maximum flow (t/h)	Variable cost (R/t)
Mill Water	1838	0.01
Domestic Water	482	0.06

5.4.3.2 Disposal cost

Solid and liquid waste disposal contribute to the cost of treatment, and therefore has to be included in the optimisation model. Each waste disposal sink has a specific disposal cost attached to it. This way, the model is forced to minimise waste in order to reduce cost. Table 5-23 shows the disposal cost used for each utility sink in the optimisation model, except the final effluent sink.

Table 5-23 Utility sink disposal costs

Utility Sink	Maximum flow (t/h)	Variable cost (R/t)
Ash Sink	-	0.20
Solid waste sink	-	0.03
RO brine sink	-	50.00
Recovery circuit sink	5	0.30

5.4.3.3 Effluent discharge tariffs

There is a possibility that the authorities may in future impose effluent discharge tariffs, in order to make it financially attractive for mills to reduce effluent rather than discharging. Therefore, the possibility of effluent discharge tariffs form part of this project (see section 5.1). Although the exact discharge tariff cost structure is not known yet, some tariffs that could possibly be expected were estimated and used for this project. Table 5-24 lists the assumptions that were made for discharge tariffs. In the optimisation model, the same tariff structure was used for all optimum-cost profiles that include effluent tariffs. For optimum-cost profiles where no tariffs are charged. these tariffs were set to zero.

Table 5-24 Effluent discharge tariffs used in optimisation model

Cost element	Cost
Volumetric discharge cost	R0.15/m^3
DWS discharge cost	R0.70/kg DWS discharged
Na discharge cost	R0.60/kg Na discharged

Obviously, changing the discharge tariffs will change the entire optimum-cost profile. However, it is believed that these costs are realistic, and that the actual tariffs would not be very different from these tariffs.

5.4.4 Other savings

The optimisation model only considers direct savings in cost, such as reduced water consumption or effluent disposal cost due to recycling. However, recycling of effluent may open many other cost saving opportunities in the mill, which are not included in the pinch analysis. Examples of these savings are:

- Reduced biocide consumption on the paper machines
- Higher paper machine running speeds due to higher headbox temperature, leading to higher production.
- Lower steam consumption due to higher system temperature
- Reduced chemicals usage

5.4.5 Cost of conventional treatment

For calculating the cost of conventional treatment, exactly the same equipment costs and general cost structure was used as in all other scenarios. All the effluent was first sent through either the clarifier or DAF, after which all the effluent was treated in a biological treatment plant and discharged. No sand-filter was used in this option, as a polishing step is not necessary if the effluent is discharged to the river.

The cost of treating all the effluent in one large biological reactor and then discharging the treated effluent makes this a relatively expensive option.

5.5 Verifying the optimisation model results using *WinGEMS*™

For this project, it was assumed that the *WinGEMS*™ simulation is representative of mill conditions. and that *WinGEMS*™ will accurately predict intermediate stream qualities as well as effluent qualities for any treatment and recycling option. The reason for this assumption is that the *WinGEMS*™ simulation was set up using actual data, and is therefore the best tool to predict changes in the mill due to effluent treatment and recycling.

Therefore, although the optimisation model was set up using *WinGEMS*™ input data, it is important to ensure that the results obtained with the *WaterPinch*™ optimisation model are the same when tested using *WinGEMS*™. Therefore, selected optimised treatment solutions obtained with the *WaterPinch*™ model were simulated in *WinGEMS*™ in order to test the accuracy of the results obtained using the optimisation model.

As the concept of obtaining optimum-cost profiles instead of one absolute optimum solution was applied in this project, it would be impractical to test every solution in each optimum-cost profile. It was therefore decided to test certain key solutions in *WinGEMS*™, and assume that if these are accurate, that all solutions are accurate.

Chapter 6 Results

6.1 Optimum-cost profiles

Optimum-cost profiles can be used to assess the impact of certain variables on the mill and the river. Figure 6-1 shows a typical optimum-cost profile, expressing cost to the mill versus DWS load to the river. The shape of this optimum cost profile is dependent on the DWS discharge limit set for the effluent in the optimisation model. It can be seen that the cost to remove DWS load does not increase linearly with decreasing DWS discharge. This is because the optimisation model takes all factors into account, including other bounds and limits set on all contaminants. An optimum-cost profile can therefore be a useful tool to evaluate the overall effects of different discharge limits on the cost to the mill.

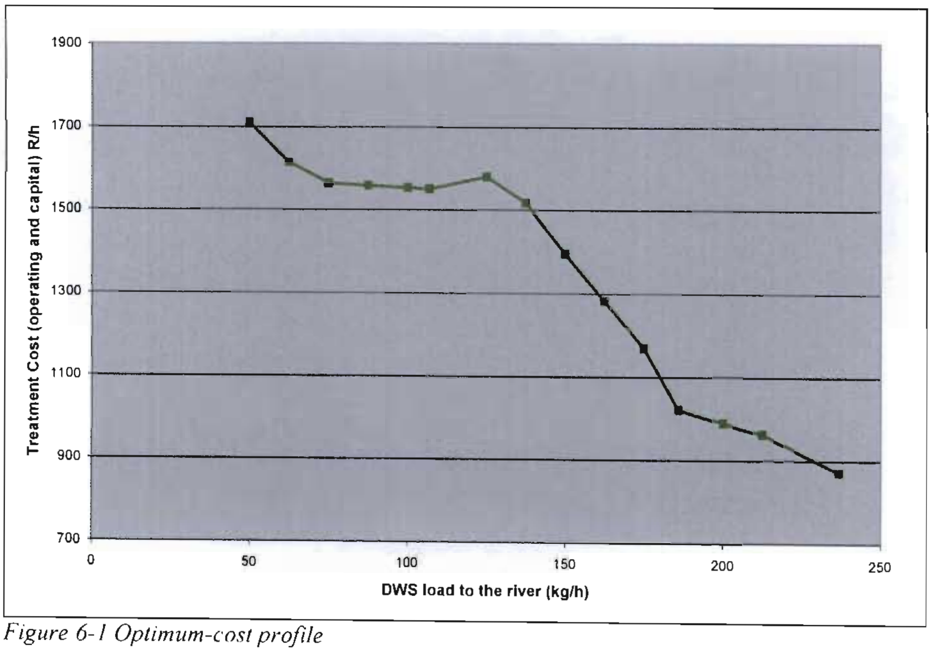


Figure 6-1 Optimum-cost profile

Each different discharge specification will have its own optimum-cost profile. Figure 6-2 shows the optimum cost profiles for a 125ppm and 150ppm effluent DWS concentration limit, expressed as a function of effluent volume.

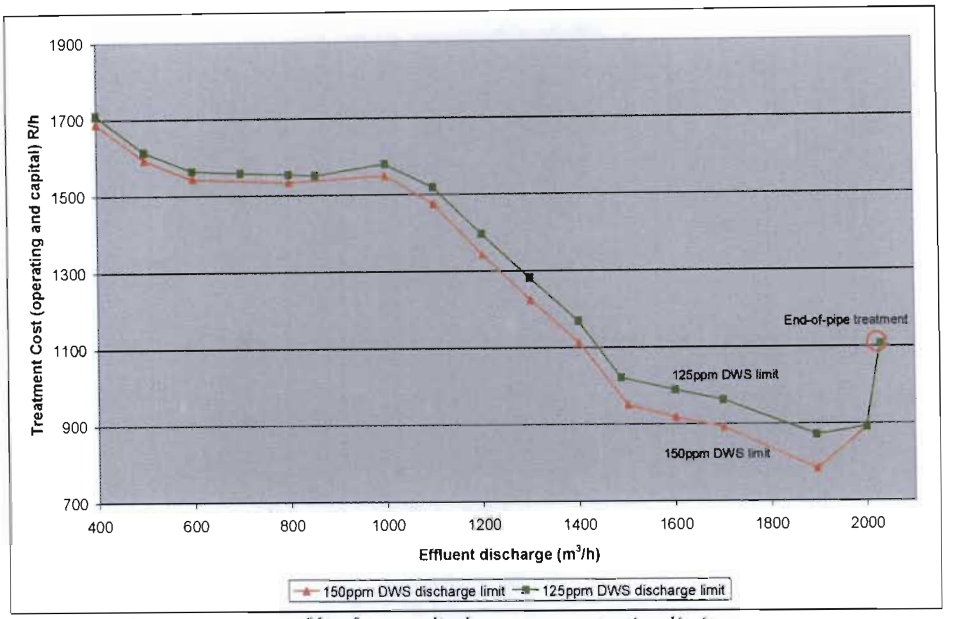


Figure 6-2 Optimum-cost profiles for two discharge concentration limits

From Figure 6-2 it can be seen that a 150 ppm discharge limit will be cheaper to achieve than a 125ppm limit. Although this result is not surprising, what is apparent from the optimum-cost profiles is that, for the same cost, the mill could reduce effluent volume if the 150ppm limit is in place. For example, for 125ppm limit, it costs the mill R872/h to discharge $1895m^3/h$ effluent. The corresponding DWS load to the river is 237kg/h. For the same cost of R872/h, with a 150ppm discharge limit, the mill could reduce effluent volume to $1735m^3/h$, with a corresponding DWS load of 260kg/h.

With this tool, the regulator can assess whether the extra 23kg/h DWS to the river is acceptable, given the fact that the water usage and effluent volume will decrease by $160m^3/h$, or 8.4%. The optimum-cost profiles can also be used by the regulatory authority and industry to reach agreement on the best strategy to be followed. For the example, the mill may agree to reduce effluent volume by $160m^3/h$ if the DWS limit could be relaxed to 150ppm.

Optimum-cost profiles obtained through water pinch analysis will be used extensively in subsequent sections to demonstrate the value of the technique and to assess the impact of various factors on the river and the mill.

6.2 Results of water pinch analysis at Tugela mill

Table 6-1 shows the current operating conditions as well as anticipated new effluent discharge limits that could form part of a new discharge licence for Tugela mill. The new licence would require a significant reduction in DWS discharged in the effluent, which would require an activated sludge biological treatment plant to achieve.

Table 6-1 Current discharge conditions and potential future discharge requirements

		Flow	Na	DWS	TSS
Current operating conditions	Effluent flow (m^3/h) and concentration (ppm)	2029	206	260 (520ppm COD)	119
	Load discharged (kg/h)	-	418	528	242
New target limit for investigation	Effluent flow (m^3/h) and concentration (ppm)	1895	260	125 (250ppm COD)	100
	Load discharged (kg/h)	-	492	237	190

Figure 6-3 shows the maximum effluent load for Na, DWS and TSS for a concentration based discharge limit. The concentration limit stays constant; hence the load of Na, DWS and TSS discharged at the flow and concentration limits decrease linearly as the effluent volume is decreased. However, for a load based limit, the concentration is allowed to rise as the effluent discharge decreases, in order to maintain a fixed load discharge. This concept is illustrated in Figure 6-4 where it can be seen that, for a load based discharge limit, the effective concentration limit rises significantly, although the load discharged stays constant.

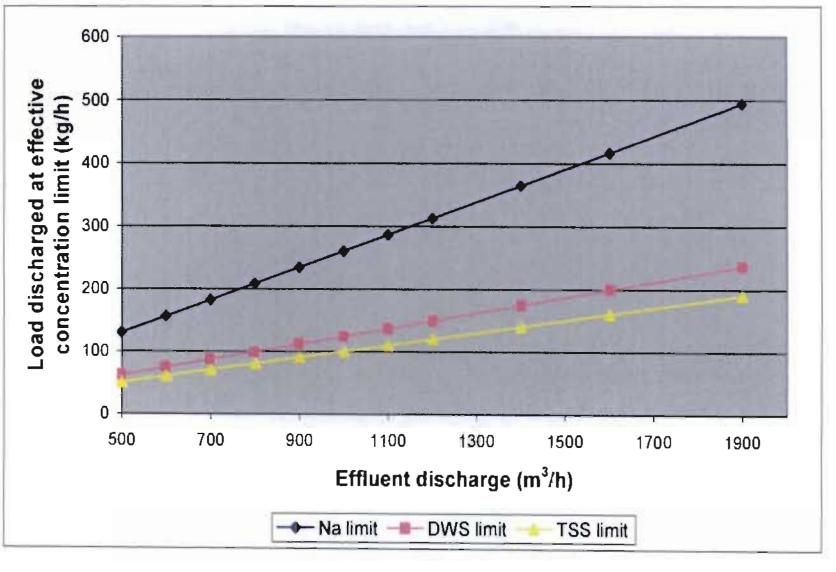


Figure 6-3 Maximum effluent load for a concentration based permit

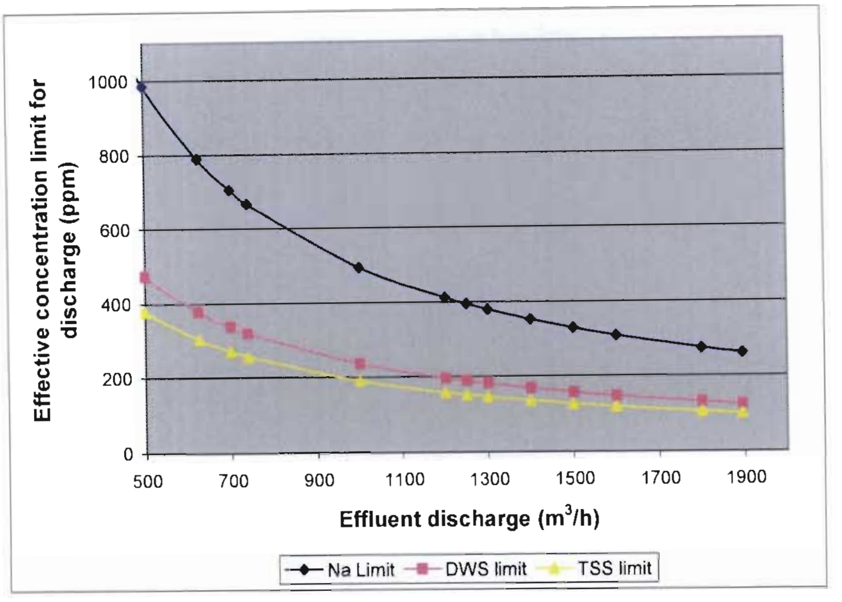


Figure 6-4 Effective effluent concentration limit for a load based permit

If we apply these limits to the effluent specifications in the water pinch model. we obtain optimum cost profiles for both a concentration based and a load based effluent discharge limit. This means that the optimisation model is used to calculate the minimum cost to treat effluent to a given effluent flow and discharge specification. whether it be concentration or load based. The model is also used to calculate the cost of conventional end-of pipe treatment for discharge. This cost is used as a reference to compare the relative costs of different treatment scenarios.

The results obtained from the model will be evaluated in terms of resulting effluent quantity and quality and in terms of cost of treatment. These two elements represent the impact on the river and the impact on the mill respectively. The benefits of a load based versus a concentration based effluent discharge limit will be illustrated in terms of the effluent quality and cost. The effect of effluent discharge tariffs will also be investigated.

The results from selected scenarios will be shown to illustrate the value of the results obtained from the water pinch model. The results obtained with the water pinch model will also be verified using the *WinGEMS*™ model.

6.3 Effluent quality

The effluent quality aspect of the water pinch model results represents the impact of the resulting effluent on the river. The effluent discharge limit determines the maximum permissible contaminant load to the river. However, the way that the effluent discharge limit is structured, whether load based or contaminant based, may have a greater impact than the actual numbers in the limit.

6.3.1 Concentration based effluent discharge limit

Figure 6-5 and Figure 6-6 show the effluent concentration and load for decreasing effluent volumes for a concentration based discharge limit. The concentration based limit forces the concentrations to low levels, regardless of the effluent discharge volume. Therefore, the load reduces linearly with decreasing effluent volume. As can be seen from Figure 6-6, the DWS concentration is always at the concentration limit, as just enough DWS is removed in the biological treatment plant to meet the effluent specifications.

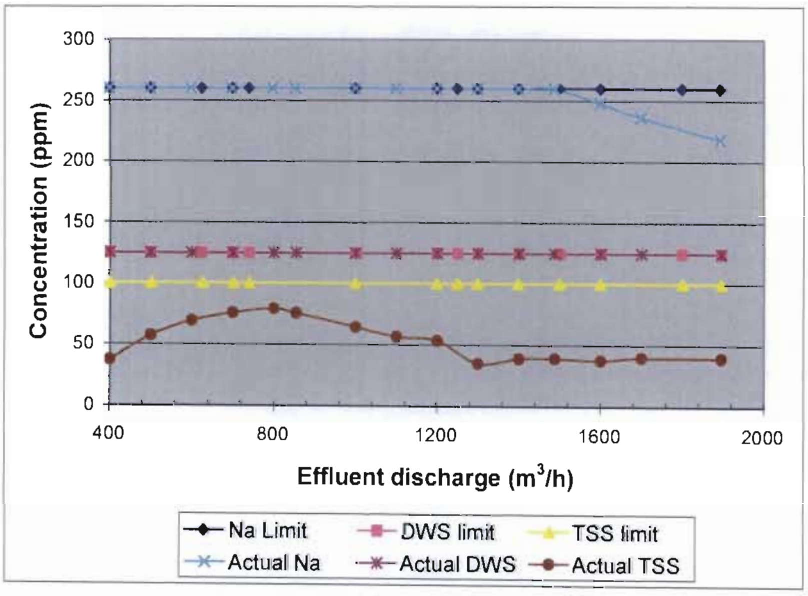


Figure 6-5 Contaminant concentration discharged for a concentration based effluent limit

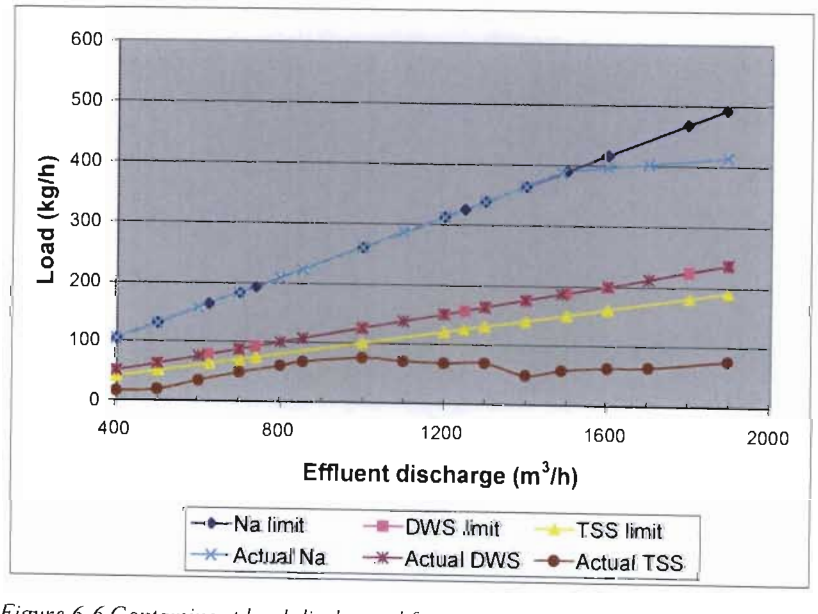


Figure 6-6 Contaminant load discharged for a concentration based effluent limit

The total solids (TSS) is always below the limit, as the clarifier, DAF and sand filter effectively remove solids from the effluent.

The sodium concentration is below the concentration limit of 260ppm at high effluent flows. However, at an effluent flow of around 1488m^3/h, the sodium concentration reaches 260ppm, which prevents further re-use of treated water without removing sodium from the effluent. This necessitates the use of reverse osmosis (RO) to remove the excess sodium from the effluent. The RO unit is sized just large enough to remove exactly the required amount of sodium to meet the specification. However, the high capital and operating cost of the RO unit causes the cost to rise significantly below effluent volumes of 1488m^3/h, which is the minimum effluent volume that can be achieved without requiring RO.

This means that below 1488m^3/h, the sodium in the effluent is the limiting component that prevents further effluent re-use, due to the effluent concentration limit. In effect, the sodium is removed in a similar way to end of pipe treatment, simply to reduce the effluent concentration and not to satisfy actual process constraints. Therefore, there is no driving force for the mill to re-use effluent and hence no real additional benefit to the river, as the mill will in effect maximise the load discharged whilst still complying with the concentration based discharge limit.

Although DWS is always at the effluent concentration limit, there is capacity for reducing DWS in the effluent relatively cheaply. Therefore, DWS is not limiting for this scenario.

6.3.2 Load based effluent discharge limit

Figure 6-7 and Figure 6-8 show the effluent concentration and load for decreasing effluent volumes, for a load based discharge limit.

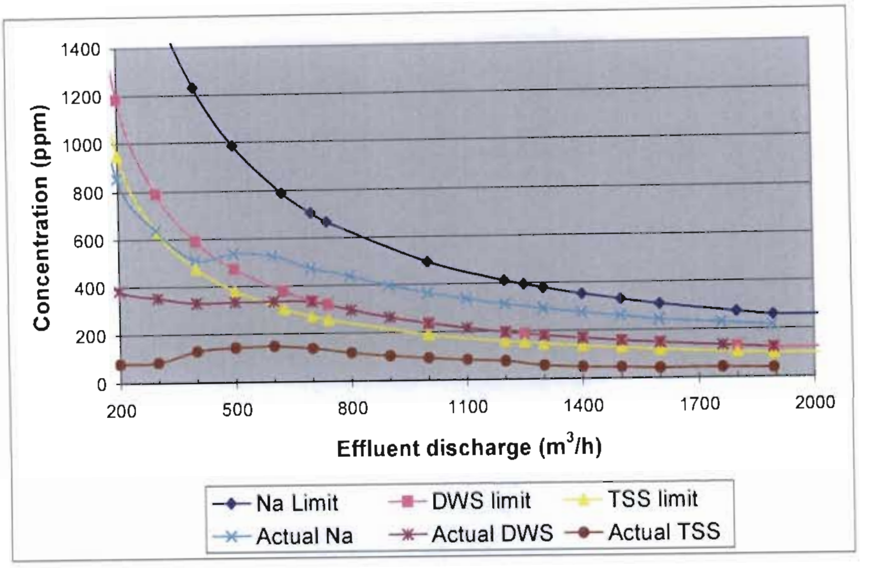


Figure 6-7 Contaminant concentration discharged for a load based effluent limit

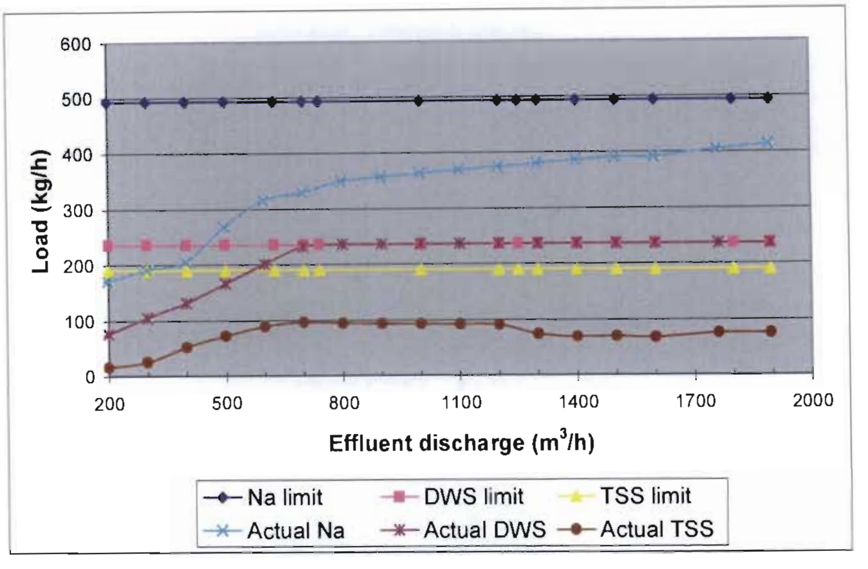


Figure 6-8 Contaminant load discharged for a load based effluent limit

From Figure 6-7 and Figure 6-8 it can be seen that the DWS follows the concentration and load limiting profiles for flows higher than 700m^3/h. However, sodium and TSS are below the limiting concentration and load. This means that the sodium load *decreases* with decreasing effluent volume, as can be seen in Figure 6-8.

The DWS concentration in the effluent is the limiting component for flows above 700m^3/h. The sodium concentration is not limiting and is below the effective concentration limit. Therefore, no expensive RO treatment for the removal of sodium is required.

At effluent flows below 700m^3/h, an interesting trend is observed. The biological effluent treatment plant size increases and therefore removes more DWS than is required to satisfy the effluent concentration limit. Hence, the effluent DWS load decreases. Although sodium is not limiting and still below the permissible effluent concentration limit, an RO unit is unexpectedly introduced by the model at just below 600m^3/h. This RO unit not only further reduces the sodium load in the effluent, but also the DWS load.

From this observation, it is clear that the effluent is no longer the limiting factor, but that some process constraint is overriding the effluent constraints. This means that the pinch constraint has moved to a process stream instead of a utility stream. The constraint in this case is the fact that the effluent cannot be reduced below 700m^3/h without reducing the domestic water flow and replacing it with an equivalent source. The only way of obtaining water of this quality is with the RO unit, which reduces both DWS and sodium concentrations to very low levels. However, when the cost aspect of this option is investigated, it will be shown that the introduction of the RO unit escalates the capital and operating cost and makes the option economically unattractive.

6.4 Cost to the mill – Optimum-cost profiles

Figure 6-9 shows the optimum cost profiles for load based and concentration based effluent discharge limits. These cost profiles were calculated using the optimisation model, and it includes operating and capital costs. For this scenario, there are no effluent discharge tariffs.

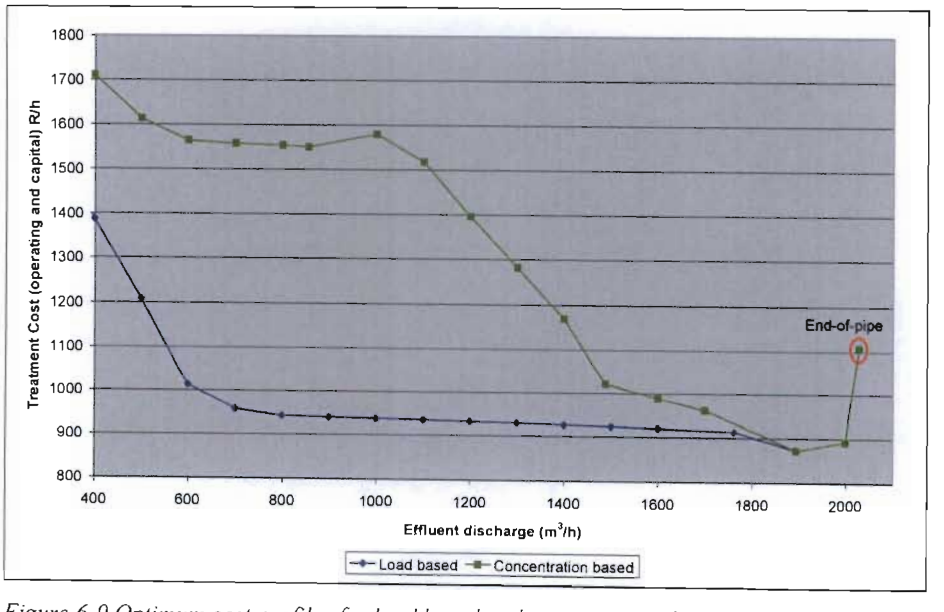


Figure 6-9 Optimum cost profiles for load based and concentration based effluent discharge limits

The first observation that is made from Figure 6-9 is that distributed effluent treatment designs obtained with the optimisation model are significantly cheaper than end-of pipe treatment for discharge. This is because the water pinch model optimises the level and combination of treatment for each effluent stream. This means that no stream is unnecessarily treated, thus minimising treatment units and saving both capital and operating cost.

From Figure 6-9, it can be seen that it is significantly cheaper to treat and recycle effluents with a load based discharge limit than for a concentration based limit. This means that there may be opportunities for the mill to reduce cost by reducing effluent discharged if a load based limit is in place, whereas the cost of reducing effluent volume increases with a concentration based limit, thus stifling any cost- or effluent saving opportunities.

6.4.1 Effluent discharge tariffs

There is a possibility that the regulatory authority will in future enforce a waste discharge tariff structure to force mills to reduce effluent volume and load. Employing the waste discharge tariffs set out in section 5.4.3.3 to the optimisation model, the optimum cost profiles in Figure 6-10 are obtained.

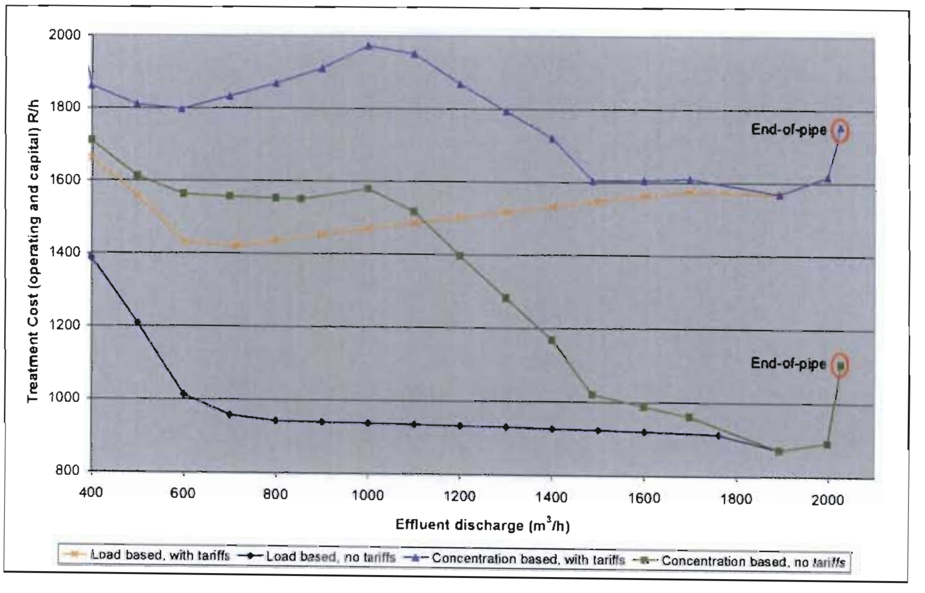


Figure 6-10 Optimum cost profiles for load and concentration based discharge limits, with and without effluent discharge tariffs

Figure 6-11 expresses the optimum cost profiles in terms of relative cost, i.e. the cost of treatment relative to the corresponding end-of-pipe treatment cost.

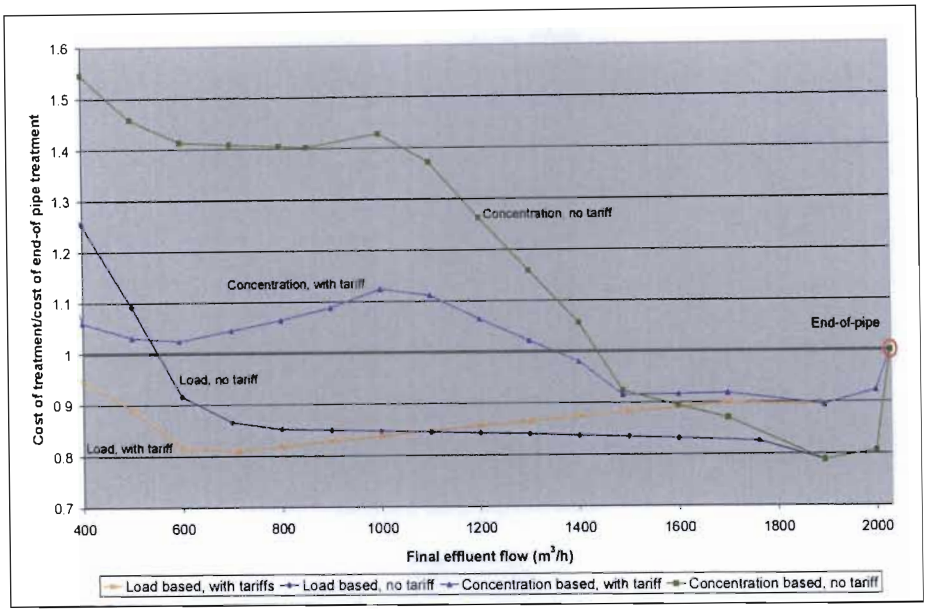


Figure 6-11 Optimum cost profiles in terms of relative cost

From Figure 6-10 and Figure 6-11 it can be seen that a discharge tariff only reduces the relative cost of treatment, but that the real cost escalates to very high levels. For a concentration based effluent discharge limit, discharge tariffs do not make it viable for the mill to reduce effluent. As can be seen from Figure 6-11, the relative cost of treatment increases for flows above 1488m^3/h when discharge tariffs are introduced. The cheapest operating point is still at 1895m^3/h, which represents no effluent re-use, as the effluent limit was set to 1895m^3/h in paragraph 6.1.

However, for a load based effluent discharge limit, the situation is the opposite. If discharge tariffs are imposed together with a load based discharge limit, the least cost option is at an effluent discharge level of 714m^3/h. This represents the lowest effluent discharge where the effluent DWS is limiting. At lower effluent discharge volumes, the process instead of the effluent becomes limiting, and an RO treatment unit is required to provide high quality water to the process.

The optimum cost profiles for each scenario provide an insight into the different costs for discharging to different effluent volumes and discharge limits. This information would be unavailable if only one optimum cost point was calculated for each scenario

6.5 Benefits of a load based effluent discharge limit

It may be argued that the river does not benefit from a load based discharge limit, as there is no load reduction on the river. However, this is not true. Up to this point, the effluent quality criteria and the cost aspect of reaching these limits were looked at separately. In order to assess the impact of load and concentration based discharge tariffs, it is necessary to look at both the effluent quality and cost aspects together.

As an example, assume that the mill wants to keep the cost of treatment at 90% of the equivalent end-of pipe treatment cost. This target of 90% is set regardless of whether the discharge limits are load based or concentration based. Therefore, from Figure 6-12, the effluent treatment scenario used will be lowest effluent point of the relative cost curve where the relative cost is 0.9.

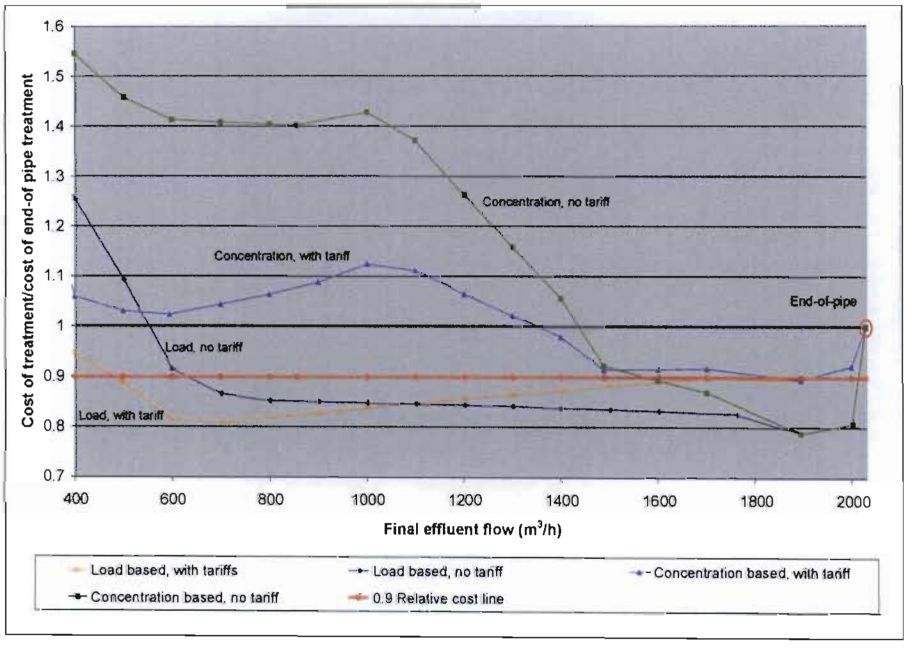


Figure 6-12 Treatment to 90% relative cost

From Figure 6-12, it can be seen that for a load based effluent discharge limit with discharge tariffs, the 90% cost point lies at 481m^3/h, and for a concentration based discharge limit with discharge tariffs, the 90% cost point lies at a much higher 1849m^3/h. Similarly, without discharge tariffs, for a load based discharge limit the 90% cost point lies at 630m^3/h, and for a concentration based discharge limit the 90% cost point lies at 1574m^3/h.

Thus, for the same relative cost, the effluent volumes and loads discharged to the river can be plotted as shown in Figure 6-13.

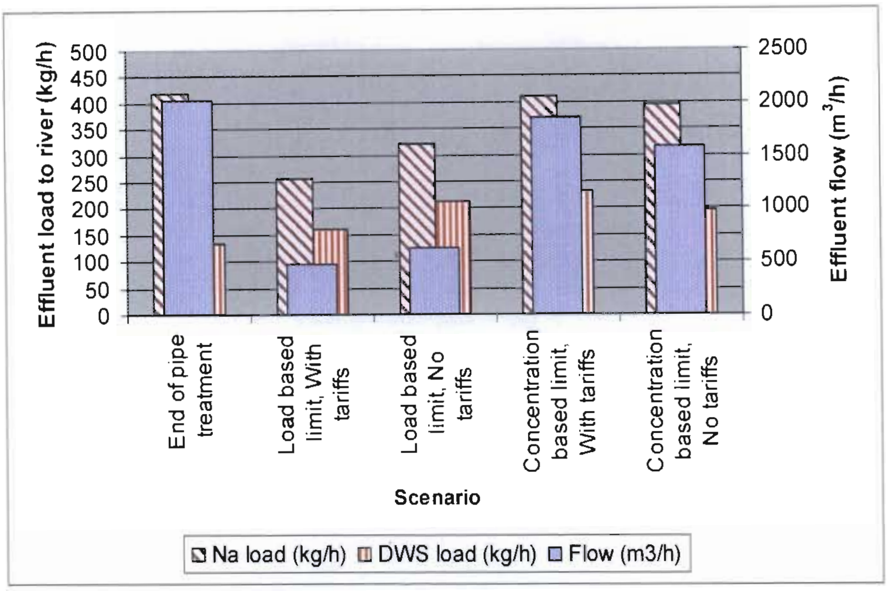


Figure 6-13 Effluent flow and contaminant load discharged for 90% relative cost

Figure 6-13 shows that with a load based limit, it is not only the effluent discharge volumes that are lower, but the sodium load discharged to the river is lower than with a concentration based limit. With effluent discharge tariffs, the DWS load to the river is lower for a load based limit than for a concentration based limit. Without tariffs, the load based limit DWS load to the river is marginally higher than for a concentration based limit.

Conversely, if one assumes that the load of DWS discharged to the river has to be constant, the results as shown in Figure 6-14 are obtained.

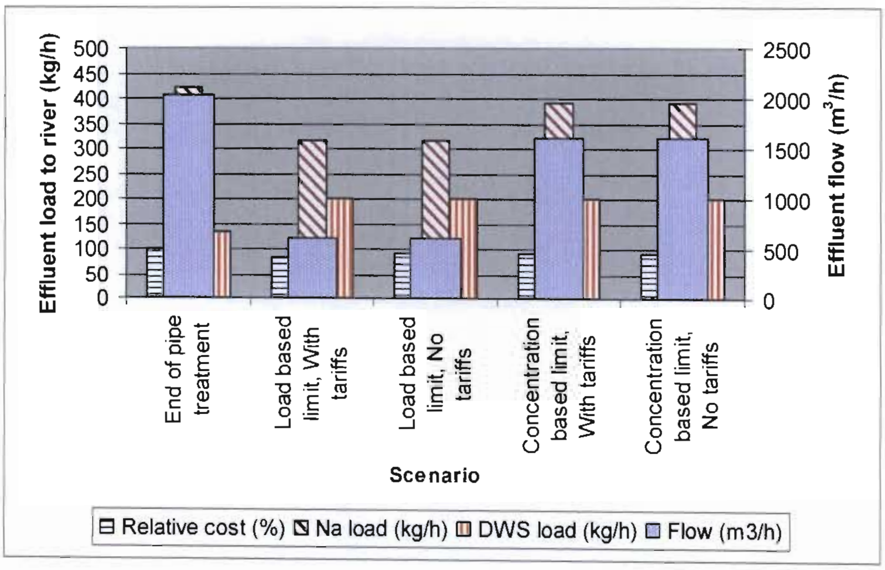


Figure 6-14 Effluent flow and contaminant load discharged to achieve a constant DWS load discharged

From Figure 6-14 it is clear that, for the same DWS load discharged to the river, the sodium load to the river is 19.4% lower for a load based limit than for a concentration based discharge limit. The effluent volume discharged for a load based limit is 62.5% lower than for a concentration based effluent limit. For this example, the relative costs for all the scenarios were less than 100%. However, this may not always be the case, especially for the concentration based effluent limit scenarios.

Figure 6-15 shows the load based and concentration based limit relative cost curves, without effluent discharge tariffs. Included on this figure is the load based and concentration based sodium discharge profiles.

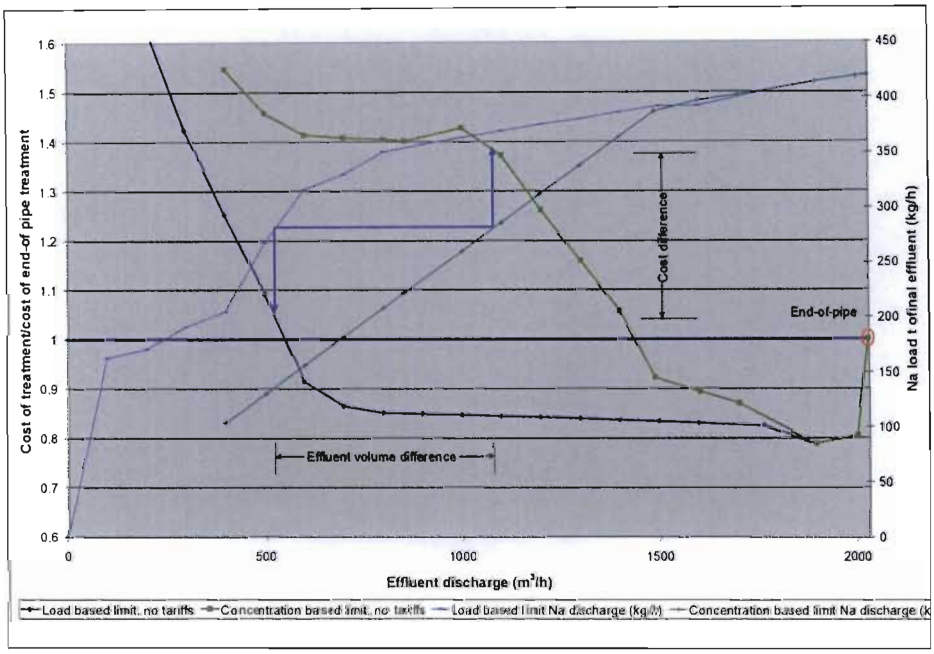


Figure 6-15 Optimum cost profiles including effluent sodium load profiles

By connecting the two sodium discharge lines at equal discharge load, one can read the corresponding relative costs of the corresponding cost curves. This graph clearly illustrates the cost and volume saving than can be achieved if a load based rather than a concentration based limit is in place.

It is also clear from Figure 6-15, as in Figure 6-8, that for a load based limit, the sodium load decreases with decreasing effluent volume, although it is allowed to stay constant.

6.5.1 Additional benefit to the river

The average flow of water in the river is approximately 19m^3/s. However, the 5 percentile flow of the river is 2.28m^3/s, and the 1 percentile flow is 1.03m^3/s. This means that at very low river flows, the mill uses a significant portion of the river water. Figure 6-16 compares the current operation with the optimum profiles for a concentration based limit and a load based limit at a 1 percentile river flow.

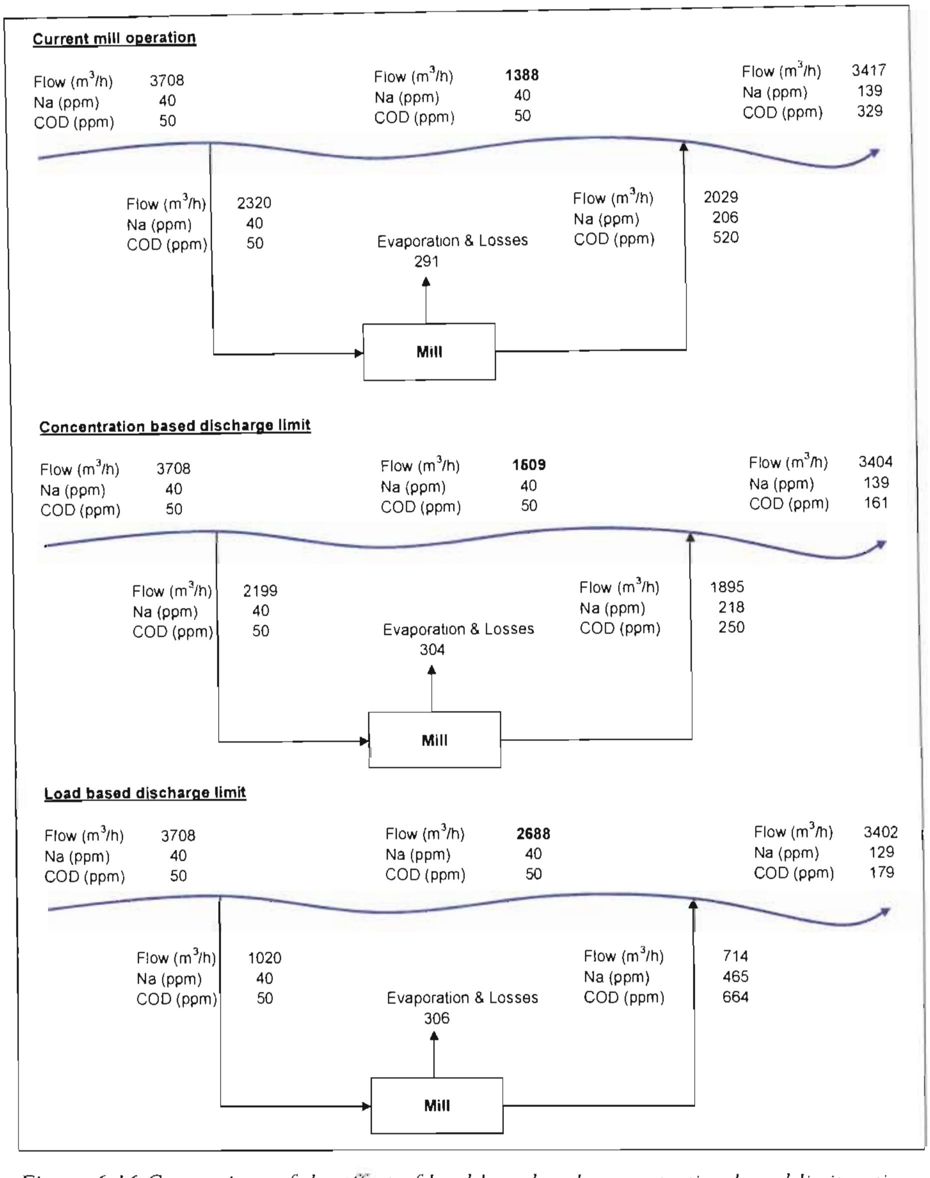


Figure 6-16 Comparison of the effect of load based and concentration based limit optimum profiles on the river at the 1 percentile river flow

From Figure 6-16 it can be seen that, at low flow conditions, the mill uses a large amount of the available river water for a concentration based discharge limit, leaving only a small amount of river water to pass through the section of river between the abstraction and discharge points. However, with a load based discharge limit that allows the mill to reduce effluent volume, the river has significantly more water flowing between the abstraction and discharge points. Both of the treatment options lead to a significant drop in the COD load discharged to the river, but only the load based limit scenario leads to a reduction in sodium load to the river.

6.6 Optimum-cost profile analysis

The optimum-cost profiles obtained with the optimisation model can be used to analyse the effects of changing certain key variables, such as discharge tariffs and operating costs. This can prove to be a useful decision-making tool for the mill in the design phase, as the possible effects of future changes is considered at this point. If a possible change is foreseen, the design can be tailored to provide an optimum solution both for the current situation and for future changes. The causes for unexpected costs can also be determined by analysing the underlying cost elements that make up the optimum-cost profile.

Therefore, optimum cost profiles can be used to do a cost-risk analysis before and during design, thus minimising the risk of extra cost to the mill.

The effects of changing certain variables will be demonstrated by analysing the optimum-cost profiles developed in section 6.4. Once again, the main variable is the load or concentration effluent discharge limit. All other effects are compared under this main variable, in order to establish which discharge limit is preferable under each condition.

6.6.1 Effect of capital and operating cost

The cost calculated by the model consists of three parts, namely capital cost, operating cost and effluent discharge cost. These three cost elements make up the total cost of treatment.

Figure 6-17 and Figure 6-18 show the capital and operating cost elements for a load based and concentration based discharge limit respectively. No discharge tariffs are in place.

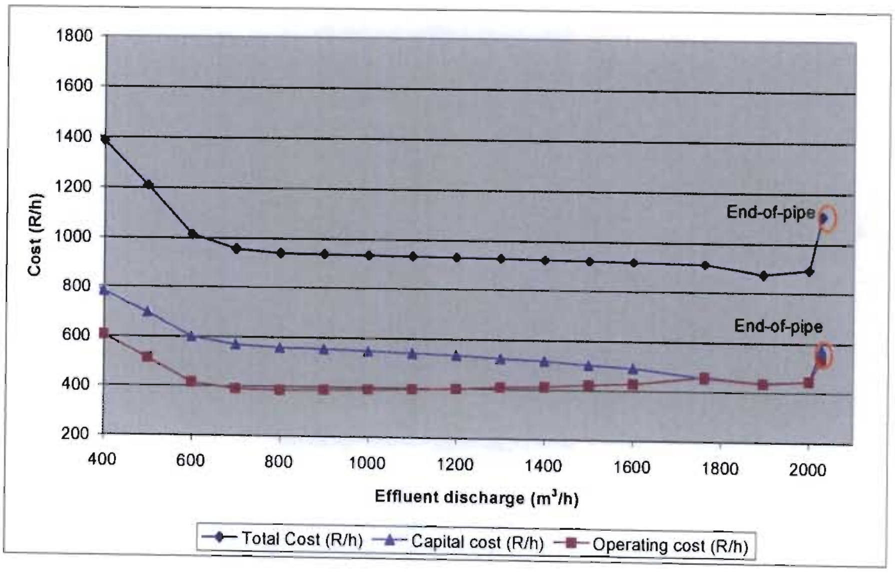


Figure 6-17 Capital and operating cost elements for a load based discharge limit, without effluent discharge tariffs

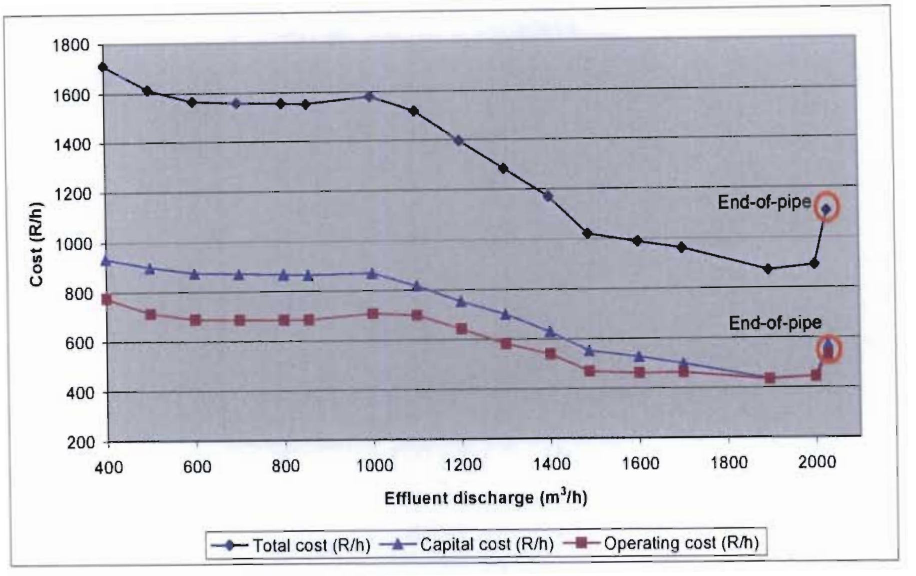


Figure 6-18 Capital and operating cost elements for a concentration based discharge limit, without effluent discharge tariffs

It is clear that a load based discharge limit allows the operating cost to be reduced with decreasing effluent volume, whilst only slightly increasing the capital investment required. There is a large range of effluent discharge volumes at which it is more cost effective for the mill to operate than to treat and discharge.

With a concentration based limit, the capital and operating cost elements generally increase with a reduction in effluent. Below $1000 m^3/h$ effluent discharge, there is a region where the cost increase flattens out; however, the total treatment cost is still excessive and not a viable option for the mill.

Figure 6-19 and Figure 6-20 show the capital, operating and effluent discharge cost elements for a load based and concentration based discharge limit respectively. Effluent discharge tariffs are in place for this scenario.

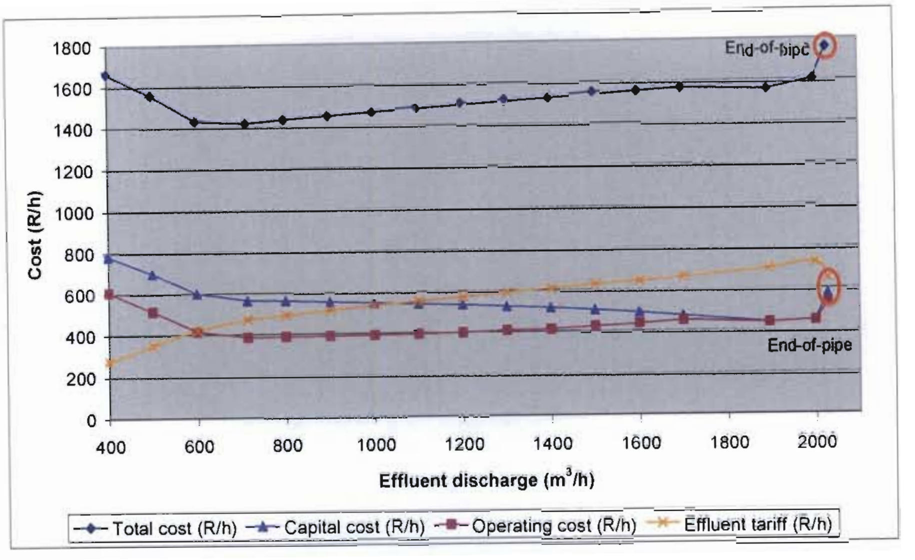


Figure 6-19 Capital, operating and effluent discharge cost elements for a load based discharge limit, with effluent discharge tariffs

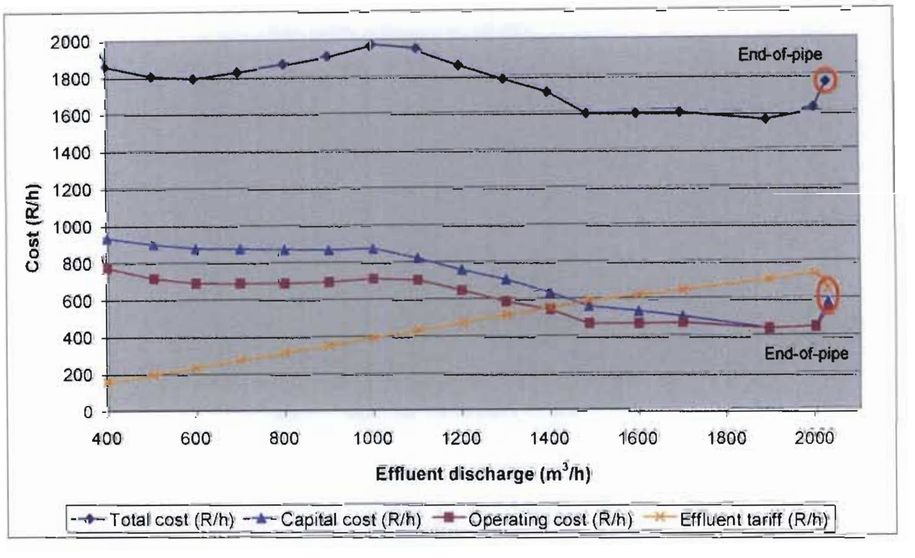


Figure 6-20 Capital, operating and effluent discharge cost elements for a concentration based discharge limit, with effluent discharge tariffs

As can be seen from Figure 6-19, the effluent discharge cost decreases with effluent volume discharged. For a load based discharge limit, this reduction in cost causes the total cost to decrease with effluent volume. However, for a concentration based discharge limit, the reduction in effluent discharge cost with decreasing effluent volume is not large enough to neutralise the rise in capital and operating cost; hence, the cost rises with reduced effluent volume, as can be seen in Figure 6-20.

6.6.2 Effect of discharge tariffs

The discharge tariff structure used in the pinch analysis is merely an estimation of what such a discharge charge structure could possibly be. At the moment, no tariffs are in place, and they may not be for some time to come. If we assume that the new licence will initially be issued without any immediate discharge tariffs, but that there is a possibility of discharge charges being enforced in future, it may pay the mill to choose an initial design that will benefit the mill in the short and the long term. Figure 6-21 and Figure 6-22 show the relative cost curves for a load based and concentration based effluent discharge limit respectively. In both figures, curves for no tariffs and effluent tariffs are shown. A third, higher cost option curve is also included in each figure. This higher cost option is a projected curve for a higher discharge tariff than the one used in the original optimisation model. The higher cost equates to double the discharge tariff used in the model.

This higher cost option may be seen as a projection of what would happen if the plant was built, after which the effluent tariffs increase. The capital and operating costs are then already in place and cannot be changed.

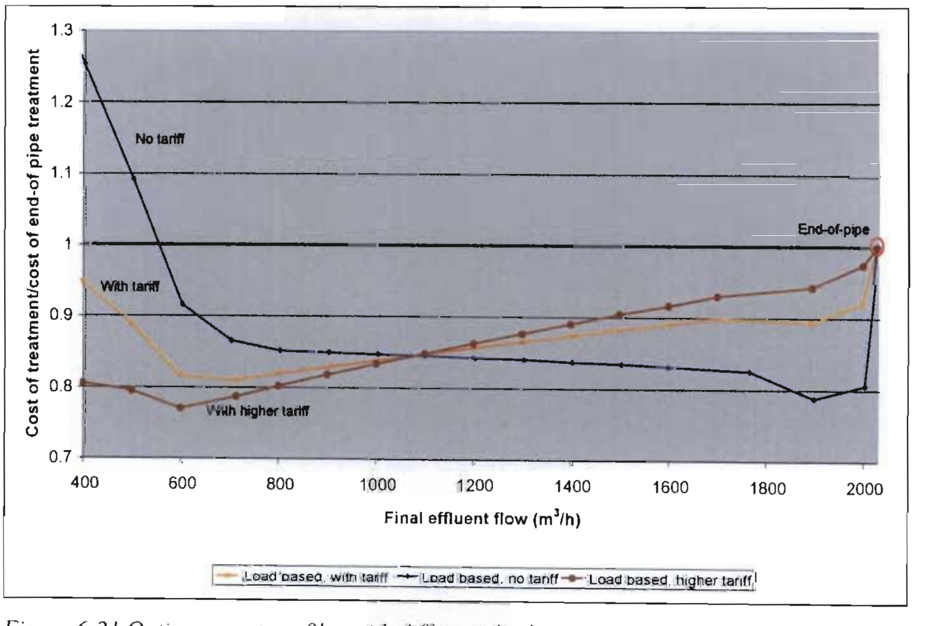


Figure 6-21 Optimum cost profiles with different discharge tariffs for a load based discharge limit

For a load based effluent discharge limit, the curves in Figure 6-21 cross over at approximately 1100m^3/h effluent flow. For effluent flow below the flow, the relative cost of treatment becomes less with the introduction of waste discharge charges. Above 1100m^3/h effluent flow, the opposite is true, with the relative cost increasing with introduction of a discharge tariffs. It would therefore benefit the mill to operate at an effluent flow of less than 1100m^3/h, as the introduction of discharge tariffs will then least affect the mill's bottom line.

For a load based effluent limit, operating below 1100m³/h is viable, as the optimum operating point lies in this region.

For a concentration based limit, Figure 6-22 shows that at effluent flows below 1488m³/h, the relative cost with discharge tariffs is lower than without discharge tariffs. For effluent flows above 1488m³/h, the relative cost increases with the introduction of discharge tariffs. From the curves it is clear that, except for cases with very high discharge tariffs, it is not viable for the mill to operate below 1488m³/h, as the costs are too high, even if the relative cost has decreased. If the mill operates at effluent levels above 1488m³/h, the costs are still lower than end-of-pipe treatment.

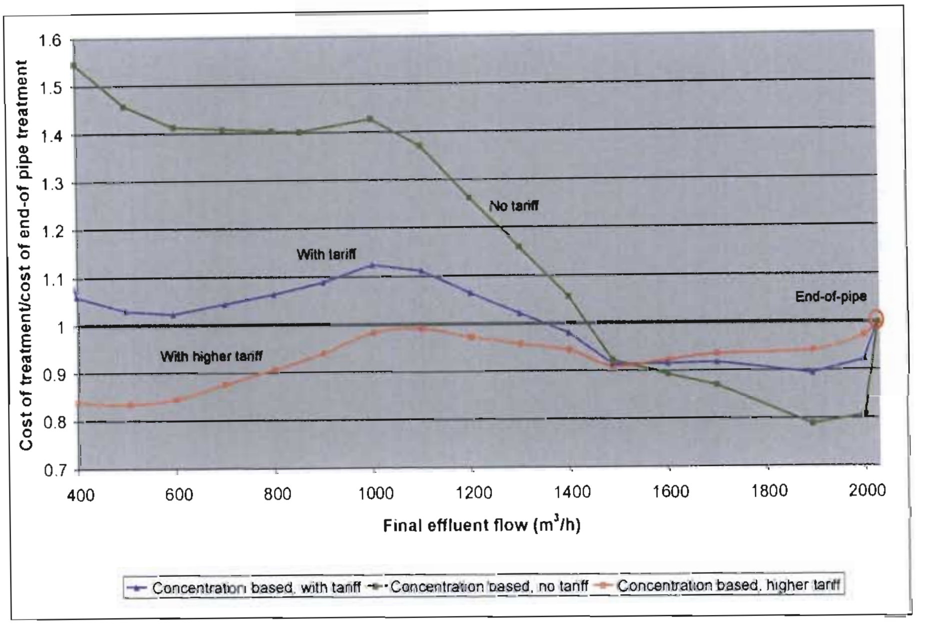


Figure 6-22 Optimum cost profiles with different discharge tariffs for a concentration based discharge limit

The relevance of this data is that for a concentration based limit, the mill will at best decrease effluent volumes to 1488m³/h. The effluent volume of 1488m³/h is the minimum effluent flow that can be achieved with a concentration based limit without having to use a RO treatment unit. This is the reason for the sudden rise in relative cost below 1488m³/h.

For a load based effluent discharge limit, there is an incentive to operate at levels below 1100m³/h, especially if there is a prospect of effluent discharge tariffs being employed. With a concentration based limit, even extremely high discharge tariffs cannot make it feasible for the mill to operate at lower effluent discharge volumes; hence the mill will do the minimum to just ensure compliance.

It must be noted that for a load based discharge limit, the effluent volume and load could be reduced further, at a lower cost, and that 1100m^3/h is the maximum operating effluent volume where the relative cost does not increase with increasing effluent discharge tariffs.

6.6.3 Effect of capital and operating cost changes

The capital and operating cost used in the water pinch analysis may be underestimated, as these costs may have escalated since costing the treatment units. From Figure 6-19 and Figure 6-20 it is clear that the capital and operating cost elements, more than the effluent discharge cost, determine the shape of the total cost curve. Therefore, assuming that the capital and operating cost will only increase, one can assume that the capital and operating cost profiles observed in Figure 6-19 and Figure 6-20 will still hold for higher capital and operating costs. With capital and operating cost escalation, the effect of discharge tariffs become less pronounced in comparison to capital and operating costs.

In general, the capital and operating costs for a concentration based discharge limit is higher than for a load based limit, and therefore the difference will become larger when the capital and operating costs escalate. For higher capital and operating costs, effluent discharge tariffs will not benefit the river, especially for a concentration based effluent discharge limit, as the main aim of the mill will be to minimise capital and operating cost, by discharging maximum effluent.

6.6.4 Effect of treatment units used

In order to better understand the results obtained with the optimisation model, it is useful to inspect the various treatment unit sizes and costs for varying effluent volumes. Once again, the results for a load based discharge limit and concentration based limit will be compared.

Figure 6-23 and Figure 6-24 show the design effluent treatment unit sizes as a function of effluent discharge volume for concentration based and load based effluent discharge limits respectively. The treatment unit size refers to the normal design flowrate of the unit. These treatment unit sizes are the same whether effluent discharge tariffs are in place or not, as the discharge permit conditions, and not the discharge tariffs, dictate the sizing of the treatment units.

In both scenarios, the biological treatment units are smaller than for an end-of-pipe treatment option.

6.6.4.1 Concentration based discharge limit

Figure 6-23 shows the treatment unit sizes calculated by the optimisation model for the optimum cost profile for a concentration based discharge limit.

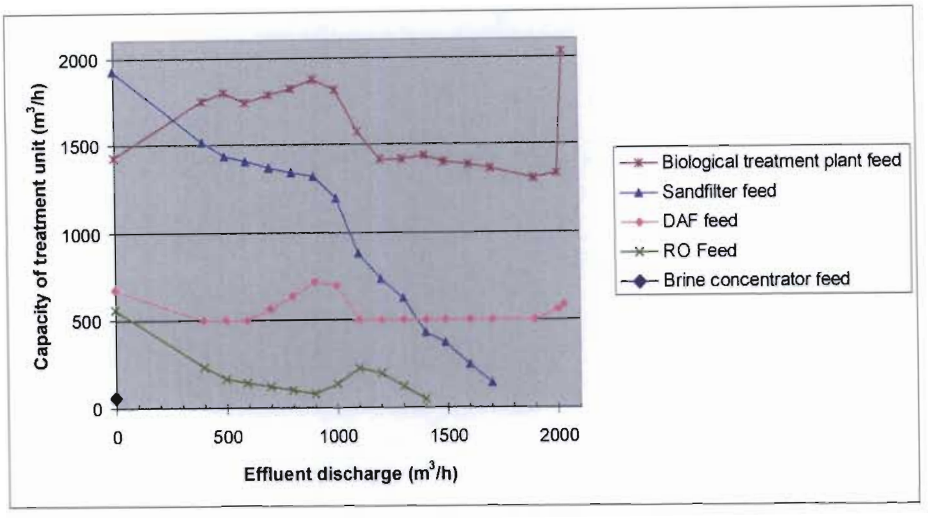


Figure 6-23 Effluent treatment unit sizes for a concentration based effluent discharge limit

In Figure 6-23. the biological treatment plant size increases slightly when reducing effluent discharge from 1895m^3/h to 1488m^3/h. As mentioned before, 1488m^3/h is the lowest effluent volume where no RO unit is required, for a concentration based limit. When the RO unit is employed at 1400m^3/h, the biological treatment plant size decreases, as the RO unit removes some DWS. thus reducing the load on the biological treatment plant. The RO plant size increases due to the increasing amount of DWS that is removed in addition to sodium. This means that the RO unit is oversized for sodium removal at this point.

However. at 1000m^3/h it becomes more cost effective to remove more DWS with the DAF and biological treatment plant. and to decrease the RO unit size. Below 900m^3/h, the RO size increases again. this time due to sodium constraints. and causes the biological treatment plant size to decrease, due to the fact that the RO unit now removes some of the DWS. From this point the RO unit size increases directly with reducing effluent volume, as the sodium limit now determines the RO unit size.

6.6.4.2 Load based discharge limit

Figure 6-24 shows the treatment unit sizes calculated by the optimisation model for the optimum cost profile for a load based discharge limit.

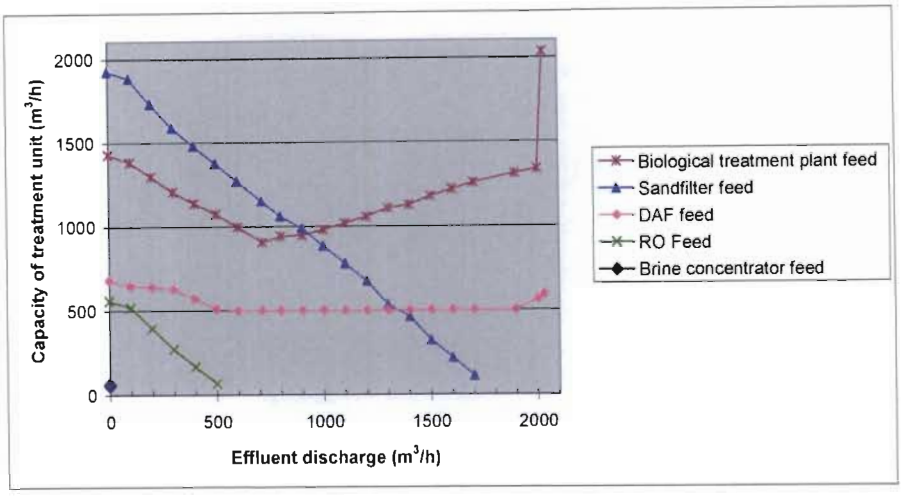


Figure 6-24 Effluent treatment unit sizes for a load based effluent discharge limit

From Figure 6-24 for a load based limit. the biological treatment plant size decreases with decreasing effluent volumes. This is because the same load of DWS is treated in a smaller treatment volume. As the cost of the biological treatment plant is related mainly to feed flow, but also to load DWS removed, the cost of the biological treatment plant will therefore decrease with reduced feed flow.

This downward trend would continue if the effluent DWS concentration remained the pinch point. However, at an effluent rate of $714m^3/h$ and less, the pinch point moves to the process, and a process utility sink. in this case domestic water DWS, becomes the pinch point. The pinch point has in fact moved to a lower DWS concentration. which is the DWS concentration of domestic water. At effluent flows below $714m^3/h$, the biological treatment plant size increases to remove more DWS. However, the biological treatment plant cannot achieve the very low pinch concentration, and therefore a RO unit is required to generate high quality water. The RO unit is sized to produce enough high purity water to supply the process demand.

It is clear that below $714m^3/h$, all the possible process sinks have been supplied with recycled effluent, and to reduce the effluent further, it would have to be regenerated to very high quality at very high cost. It is therefore not feasible for the mill to operate at effluent volumes of less than approximately $600m^3/h$, where an RO unit is needed.

6.7 Results for selected scenarios

In this section, the resulting distributed effluent treatment designs are shown in more detail. Due to the number of runs that were done, only selected key scenarios will be discussed. However. a unique optimised design, calculated by the optimisation model, exists for every scenario that was run.

6.7.1 Base case scenario

Figure G-1 in Appendix G shows a layout drawing of the base case scenario. As can be seen, no effluent treatment is in place, except for the two existing effluent clarifiers.

6.7.1.1 Cost elements

Table 6-2 summarises the cost elements for the base case scenario. The operating cost is mainly due to the clarifier operating cost, as well as water costs. The effluent discharge cost is high due to the high effluent volume and contaminant load.

Table 6-2 Cost elements for the base case scenario

Capital Cost		
Capital cost annualised and total	-	
Operating cost		
Operating cost, excluding discharge tariffs	R219 /h	R 1 918 440 /a
Effluent cost		
Effluent discharge cost, assuming discharge tariffs	R925 /h	R 8 103 000 /a
Total Cost		
Total cost, annualised, assuming discharge tariffs	R1144 /h	R 10 021 440 /a

6.7.2 Least cost option with no discharge tariffs, 1895m^3/h effluent volume

Figure G-2 in Appendix G shows a layout drawing of the least cost scenario, with an effluent volume of 1895m^3/h. Only a biological treatment plant and DAF unit is used for this scenario. The effluent consists of a blend of NSSC pulping hot water, demineralisation plant regeneration effluent, Clarifier 1 overflow and biological treatment plant effluent. The biological treatment plant is sized to remove just enough DWS to ensure that the effluent specifications are met.

This option is identical for both a load based and effluent based discharge limit.

6.7.2.1 Cost elements

Table 6-3 summarises the cost elements for the least cost option with no discharge tariffs. The capital cost is mainly due to the biological effluent treatment plant. As no significant effluent recycling takes place in this scenario, no sand-filter is required. This is the reason for the low relative cost of this scenario.

Although the effluent discharge cost for this scenario is zero, if implemented later, effluent discharge costs will be very high due to the high effluent volume and contaminant load. If effluent discharge tariffs are a real possibility, this option will be expensive in the long run, although it may be the cheapest in the short term.

Table 6-3 Cost elements for the least cost option with no discharge tariffs

Capital Cost		
Biological treatment plant, combined	R 29 121 124	
Dissolved Air Flotation	R 3 452 287	
Sand-filter	-	
Reverse osmosis	-	
Total capital cost	**R 32 573 411**	
Capital cost, annualised	R437 /h	R 3 828 120 /a
Operating cost		
Operating cost, excluding discharge tariffs	R435 /h	R 3 810 600 /a
Effluent cost		
Effluent discharge cost, no discharge tariffs	-	-
Effluent discharge cost, assuming discharge tariffs	*R698 /h*	*R 6 114 480 /a*
Total Cost		
Total cost, annualised, no discharge tariffs	R872 /h	R 7 638 720 /a
Total cost, annualised, assuming discharge tariffs	*R1570 /h*	*R 13 753 200 /a*

6.7.3 Concentration based limit, 1488m^3/h effluent volume

Figure G-3 in Appendix G shows a layout drawing of the scenario where the relative cost curves for a concentration based discharge limit cross over, as explained in Figure 6-22, paragraph 6.6.2. At this point, the relative treatment cost stays constant, regardless of whether effluent discharge tariffs are implemented. At effluent flows below this point, the relative treatment cost is reduced if discharge tariffs are implemented. This point represents the lowest effluent volume where no RO treatment unit is required.

In this scenario, the biological treatment plant is divided into two separate parts, the clean and dirty side. The dirty side treated effluent is discharged, but a part of the clean side treated effluent is taken to a sand-filter, where it is filtered and recycled.

In this option, the final effluent is a blend of clean and dirty side biological treatment plant treated effluent, and Clarifier 1 overflow. Due to the concentration based discharge limit, the biological treatment plants have to handle a large feed flow to remove excess DWS. This treated effluent can not be recycled, as the concentration limit will be exceeded.

6.7.3.1 Cost elements

Table 6-4 summarises the cost elements for the concentration based limit cross-over scenario. The capital cost is mainly due to the biological effluent treatment plant, but a relatively expensive sand-filter is also required for this scenario.

Table 6-4 Cost elements for the concentration based limit cross-over scenario

Capital Cost		
Biological treatment plant, combined	R 30 538 475	
Dissolved Air Flotation	R 3 452 287	
Sand-filter	R 7 424 892	
Reverse osmosis	-	
Total capital cost	**R 41 415 654**	
Capital cost, annualised	R555 /h	R 4 861 800 /a
Operating cost		
Operating cost, excluding discharge tariffs	R464 /h	R 4 064 640 /a
Effluent cost		
Effluent discharge cost, no discharge tariffs	-	-
Effluent discharge cost, assuming discharge tariffs	*R586 /h*	*R 5 133 360 /a*
Total Cost		
Total cost, annualised, no discharge tariffs	R1019 /h	R 8 926 440 /a
Total cost, annualised, assuming discharge tariffs	*R1605 /h*	*R 14 059 800 /a*

For this scenario, the operating cost is lower than the capital cost. As expected, the implementation of discharge tariffs increases the cost substantially; however, the relative cost of treatment stays constant. To achieve the same effluent volume for a load based discharge limit would require a capital outlay of R 37 378 135, which is 10% lower than for a concentration based limit.

6.7.4 Load based limit, 1100m³/h effluent volume

Figure G-4 in Appendix G shows a layout drawing of the scenario where the relative cost curves for a load based discharge limit cross over, as explained in Figure 6-21, paragraph 6.6.2. At this point, the relative treatment cost stays constant, regardless of whether effluent discharge tariffs are implemented. At effluent flows below this point, the relative treatment cost is reduced if discharge tariffs are implemented. It would therefore benefit the mill to operate at or below this effluent volume, if possible, if the implementation of effluent discharge tariffs is expected.

In this scenario, the effluent is a blend of biological treatment plant effluent, Clarifier 1 overflow, belt-press filtrate and demineralisation plant regeneration effluent. The regeneration plant effluent, which is high in sodium, is discharged directly to the final effluent as sodium is below the limit for this scenario. The biological treatment plant is sized to remove the required amount of DWS to comply with the effluent DWS limit, which is limiting for this scenario. The sand-filter is sized to filter effluent that is recycled back to the process.

6.7.4.1 Cost elements

Table 6-5 summarises the cost elements for the load based limit cross-over scenario. The capital cost is mainly due to the biological effluent treatment plant, but a relatively expensive sand-filter is also required for this scenario.

Table 6-5 Cost elements for the load based limit cross-over scenario

Capital Cost		
Biological treatment plant, combined	R 24 623 918	
Dissolved Air Flotation	R 3 452 287	
Sand-filter	R 12 192 487	
Reverse osmosis	-	
Total capital cost	**R 40 268 692**	
Capital cost, annualised	R540 /h	R 4 730 400 /a
Operating cost		
Operating cost, excluding discharge tariffs	R395 /h	R 3 460 200 /a
Effluent cost		
Effluent discharge cost, no discharge tariffs	-	-
Effluent discharge cost, assuming discharge tariffs	*R552 /h*	*R 4 835 520 /a*
Total Cost		
Total cost, annualised, no discharge tariffs	R935 /h	R 8 190 600 /a
Total cost, annualised, assuming discharge tariffs	*R1487 /h*	*R 13 026 120 /a*

For this scenario, the operating cost is much lower than the capital cost. As expected, the implementation of discharge tariffs increases the cost substantially; however, the relative cost of treatment stays constant. To achieve the same effluent volume for a concentration based discharge limit would require a capital outlay of R 61 032 564, which is 52% higher than for a load based limit.

6.7.5 Load based limit, optimum cost scenario with effluent discharge tariff, 714m^3/h

Figure G-5 in Appendix G shows a layout drawing of the optimum cost load based discharge limit scenario. At this point, the total cost is at its lowest point for a load based discharge limit with discharge tariffs in place.

For this scenario, the effluent consists of a blend of DAF underflow, belt-press filtrate and Clarifier 1 overflow. Significantly, in this scenario, the biological treatment plant does not discharge to final effluent. This means that no secondary treated effluent is discharged to effluent, but that just enough effluent is biologically treated to satisfy the need for recycled effluent in the process. The DAF and Clarifier 1 are capable of achieving the load based discharge limit without the biological treatment plant.

The sand-filter is required to filter a large volume of biologically treated effluent that is recycled to the process.

6.7.5.1 Cost elements

Table 6-6 summarises the cost elements for the optimum load based limit scenario, including effluent discharge tariffs. The capital cost of the biological effluent treatment plant is at its lowest in this scenario. The sand-filter has to filter a large amount of treated effluent to make it suitable for recycling, hence the high cost for the sand-filter.

Table 6-6 Cost elements for the optimum load based limit scenario, including effluent discharge tariffs

Capital Cost		
Biological treatment plant, combined	R 22 753 494	
Dissolved Air Flotation	R 3 452 287	
Sand-filter	R 15 832 985	
Reverse osmosis	-	
Total capital cost	**R 42 038 767**	
Capital cost, annualised	R564 /h	R 4 940 640 /a
Operating cost		
Operating cost, excluding discharge tariffs	R386 /h	R 3 381 360 /a
Effluent cost		
Effluent discharge cost, no discharge tariffs	-	-
Effluent discharge cost, assuming discharge tariffs	R472 /h	R 4 134 720 /a
Total Cost		
Total cost, annualised, no discharge tariffs	*R950 /h*	*R 8 322 000 /a*
Total cost, annualised, assuming discharge tariffs	R1422 /h	R 12 456 720 /a

For this scenario, the operating cost is minimised and significantly lower than the capital cost. Due to the low effluent volume discharge, the effluent discharge cost is also relatively low, compared to R698/h for the 1895m^3/h scenario. To achieve the same effluent volume for a concentration based discharge limit would require a capital outlay of R 65 025 591, with an operating cost of R6 009 360/a, which is 55% and 78% respectively higher than for a load based limit.

6.7.6 Zero-effluent scenario

Thus far, the zero-effluent scenario has not been considered. The reason for this is that the zero-effluent scenario is prohibitively expensive. The zero-effluent scenario is included for the sake of completeness.

Figure G-6 in Appendix G shows a layout drawing of the optimum cost load based discharge limit scenario. No effluent is allowed to be discharged to the effluent sink. However, an RO brine disposal sink is available, but at a great cost. A brine concentrator is also available to concentrate the RO brine. A portion of this concentrate is allowed to be returned back into the recovery section of the mill to recover sodium.

As can be seen from Figure G-6, the brine concentrator size is minimised so as to produce just enough concentrate to be returned to the recovery circuit. The rest of the un-concentrated RO brine is distributed into the process, where allowed.

All domestic water is replaced by RO permeate or concentrator clean condensate. However, although the effluent volume is zero, there is still an amount of mill water used in this scenario. Because of losses in the process, an amount of mill water will always be required as make-up to the system.

6.7.6.1 Cost elements

Table 6-7 summarises the cost elements for the zero-effluent scenario. The capital cost of the biological effluent treatment plant, sand-filter and reverse osmosis plant is very high for this scenario. The cost of the brine concentrator is very high considering the small volume treated.

Table 6-7 Cost elements for the zero-effluent scenario

Capital Cost		
Biological treatment plant, combined	R 30 885 220	
Dissolved Air Flotation	R 4 236 578	
Sand-filter	R 22 334 650	
Reverse osmosis	R 20 631 388	
Brine Concentrator	R 5 087 693	
Total capital cost	**R 83 175 530**	
Capital cost, annualised	R1115 /h	R 9 767 400 /a
Operating cost		
Operating cost, excluding discharge tariffs	R3410 /h	R 29 871 600 /a
Effluent cost		
Effluent discharge cost	-	-
Total Cost		
Total cost, annualised	R4525 /h	R 39 639 000 /a

From Table 6-7 it can be seen that, although the capital cost is very high, it is the operating cost that makes this option financially unattractive. The operating cost escalates mainly due to the brine concentrator and reverse osmosis units, which both have high operating cost elements. Therefore, for this mill, zero effluent is not viable, even for extremely high effluent discharge tariffs.

6.8 Verification of results with *WinGEMS*™ model

In order to verify the results obtained with the optimisation model in *WaterPinch*™, the distributed effluent treatment designs obtained with the model were tested using the *WinGEMS*™ simulation. As it would be impossible to test every scenario generated for obtaining the optimum cost profiles of a load based and concentration based discharge limit, it was decided to test only a few key scenarios in *WinGEMS*™.

Table E-1 to Table E-6 in Appendix E show the verification results for the selected scenarios. The *WaterPinch*™ model results are compared with the corresponding *WinGEMS*™ results and the percentage deviation of the water pinch model results with respect to the *WinGEMS*™ results are shown.

As can be seen from the tables in Appendix E the optimisation model results correspond very well with the *WinGEMS*™ results. Therefore, the results generated by the optimisation model are assumed to be accurate and that the mass transfer equations derived from *WinGEMS*™ for use in the optimisation model are valid.

Chapter 7 Discussion

7.1 Optimum-cost profiles

Optimum-cost profiles obtained using water pinch analysis is a useful tool to the mill, as the lowest cost option for any given discharge limit can be found. Also, through the risk analysis component of the water pinch analysis, the mill can also assess the impacts of possible future threats on the optimum solution. This way, the design of and effluent treatment network can be tailored to minimise the impact of future changes in regulations or environmental costs, thus becoming a risk management tool for the mill.

Optimum-cost profiles also have the potential to be a decision making tool, helping the regulator to structure discharge limits in such a way that it will encourage industry to treat and recycle effluent, and hence further reducing the load on the river. The mutual understanding of the problem between the parties will minimise the likelihood of unexpected regulatory discharge limits being imposed.

7.2 Load versus concentration based effluent discharge limits

From the results it is clear that a load based limit is of benefit to the mill and the river, as the mill may have a cost incentive to reduce effluent volume with a load based limit. The secondary benefit of a load based limit is that the sodium and TSS load discharged to the river is less than the maximum allowable load, for the whole range of effluent discharge volumes.

Although effluent discharge tariffs increase the cost to the mill, they do not necessarily encourage the mill to reduce effluent volume and contaminant loads. With a concentration based discharge limit, the mill would still prefer to pay the discharge limit rather than reduce effluent volume and load, due to the fact that the cost of treatment (capital and operating) outweighs all but the most exorbitant discharge tariffs.

However, with a load based discharge limit in place, there is an incentive for the mill to reduce effluent load and volume, as the capital and operating cost for a load based limit is much lower than for a concentration based limit.

The underlying reason for the difference between the costs for a load based and a concentration based limit is the fact that a concentration based limit forces the mill to treat for discharge, whereas a load based limit allows the mill to treat for recycling, whilst still complying with, and even achieving values lower than the discharge limit.

7.2.1 Limiting component

For a concentration based discharge limit, the effluent sodium concentration is the limiting component, and therefore RO desalination is required at relatively high effluent volumes, to keep the effluent sodium concentration below the effluent concentration limit. However, for a load based limit, the effluent DWS concentration is limiting, whilst the sodium concentration stays below the limit. As DWS is cheaper to remove than sodium, this means that it is cheaper to comply with a load based limit than a concentration based discharge limit.

For a load based limit, at low effluent volumes (below $600m^3/h$) a process stream instead of the effluent becomes limiting, and therefore an RO unit is required to comply with the new limiting component.

7.2.2 Benefits of load based discharge limit to the river

It was also shown that to achieve the same effluent DWS load for a concentration based and a load based discharge limit, the cost for the concentration based limit option is always higher than for the corresponding load based limit option. Furthermore, with the load based limit option, the corresponding effluent volume and sodium load discharged is also lower than for the concentration based limit option. Therefore, with a load based limit, the mill could achieve the same DWS load discharged at a lower cost, whilst also producing a lower effluent volume and lower sodium load to the river.

There may be concern that a load based limit may cause a point source of very high concentration effluent that may be detrimental to the river at the discharge point. Although this may be true to some extent, if we assume that the mill will only treat to the optimum load based limit effluent discharge volume of $714m^3/h$, the DWS concentration of the effluent will be 332ppm, the sodium concentration 465ppm and the TSS concentration 138ppm. The current concentrations of DWS, sodium and TSS are 260ppm, 206ppm and 119ppm respectively. These values do not differ substantially from the concentrations currently discharged, and as the volume and load discharged is lower, it can be assumed that the effluent will be dispersed into the river flow quicker than is currently the case. There is also an option to use river water to pre-dilute the effluent prior to final discharge. However, this river water should not be seen as abstraction and discharge by the mill, but merely a practical solution to avoid high concentration at the discharge point.

A secondary benefit to the river is the fact that more water is allowed to pass between the abstraction and discharge point for an optimum load based limit profile than for a concentration based limit profile. This is especially valuable in times of drought when the mill uses a significant portion of the available river water.

7.3 Other possible savings and risks

It has been demonstrated that water pinch analysis can be used to do basic risk analysis through the use of optimum cost profiles. This gives the mill a tool with which to manage the risk to the mill whilst still minimising cost.

There are, however. several other savings and risks that have not been included in the pinch analysis, as this would over-complicate the analysis. The most important potential saving is the energy savings due to the recycling of effluent, especially to the paper machines. However, there is also a potential risk when increasing the temperature in a paper machine, which may lead to increased chemical usage.

Product quality deterioration is a risk when using recycled effluent instead of fresh water. This risk has to be taken into account when setting the optimisation model constraints, so as to limit the effects to an acceptable level.

Process chemicals will be recovered due to recycling of effluent. although not necessarily to the appropriate places in the process. For instance, recycling sodium to the recovery circuit will have benefits, whereas recycling sodium to the paper machine will not have benefits, but may have a potential risk.

The optimisation model assumes that all constraints have been set taking potential risks into consideration. Therefore, an understanding of the process is imperative when doing a water pinch analysis.

In reality, after an optimum cost profile has been obtained with the optimisation model, the selected optimum scenario has to be investigated in more depth to identify possible fatal flaws in the design. There may also be additional benefits that were not identified by the optimisation model.

7.4 Verification of results

From the results obtained, it is clear that the *WinGEMS*™ model data can be accurately represented in the optimisation model. However, it is important to note that extracting the data from the model into the optimisation model requires a certain amount of process knowledge and knowledge of the *WinGEMS*™ model. Furthermore, setting bounds in the water pinch optimisation model can only be safely performed with an amount of process knowledge.

The selection of treatment units is also a factor that can influence the results obtained with the water pinch model. Ideally, one should use actual pilot plant data and good cost estimates when specifying treatment unit performance and costs in for the water pinch model.

7.5 Applicability of results

The results obtained with the water pinch model have to be practically feasible. When looking at the flowsheets of the various options in Appendix G , one can see that the resulting designs are not overly complex, due to the fact that the amount of small streams allowed to be recycled have been restricted. The complexity in the design stems only from the layout of the effluent treatment units to achieve the optimum effluent quality at the minimum cost. Recycling of treated effluents back into the mill is relatively simple.

7.5.1 Applicability of water pinch analysis in the pulp and paper industry

The water pinch analysis approach should be applicable to other pulp and paper mills. The optimisation model will be unique to the specific mill and its operating conditions. Also, the treatment units needed may be different. However, a load based effluent limit should always give the mill more cost effective options than a concentration based limit.

Once again, the water pinch analysis should be undertaken by someone who has a good knowledge of the pulp and paper industry, as well as effluent treatment and recycling. Specific mill knowledge is also important, and the pinch analysis should be done in consultation with the mill's technical personnel.

In this study, water pinch analysis was used to get a top-level understanding of the major cost implications of different treatment options. The results illustrate very clearly the potential benefit of a well designed effluent regulation strategy, and that imposing effluent discharge tariffs without setting the correct discharge limits will lead to an unsatisfactory social, economical and environmental outcome for the region.

Chapter 8 Conclusions and Recommendations

The following conclusions can be drawn from the study:

- The water pinch technique is an accurate way of representing the actual mill water users and effluent generators. provided that the mass transfer relationships are correctly set up.

- The *WinGEMS*™ simulation provides the mass transfer relationships used in the water pinch model. The results obtained by the water pinch model using this method have been verified using the *WinGEMS*™ mill simulation.

- Optimum-cost profiles can be used as a transparent tool for the regulatory authority and the industry to understand constraints on the mill and the river, and to negotiate solutions that address these constraints optimally.

- Optimum-cost profiles provide an insight into subtle changes occurring with decreasing effluent volume or load. This would not be possible if only one optimum solution was found.

- Water pinch analysis finds distributed effluent treatment solutions that are less costly than end-of pipe treatment and discharge. Distributed effluent treatment often includes some form of effluent treatment and recycling. which reduces effluent volume.

- A load based limit is of benefit to the mill and the river, as the mill may then have a cost incentive to reduce effluent volume. The secondary benefit of a load based limit is that the sodium and TSS load discharged to the river is *less* than the maximum allowable load, for the whole range of effluent discharge volumes.

- Imposing effluent discharge tariffs without setting the correct discharge limits will not add financial incentive to the mill to reduce effluent volume and contaminants. However, with the correct discharge limit, effluent discharge tariffs will make it economically viable for the mill to treat and recycle effluent.

- An understanding of the process is imperative when doing a water pinch analysis. Setting incorrect bounds, concentration limits and costs can have severe consequences for the mill.

The following recommendations can be made:

- It is recommended that the technique be expanded to include energy pinch, as this could have a major cost benefit to the mill.

- The technique should be implemented at a mill on a trial basis, and the results of this trial should be used to set up a procedure on how to obtain optimum cost profiles using water pinch.

- The use of water pinch and optimum-cost profiles is not a once-off optimisation with only one result, but rather part of a process that is followed to obtain a satisfactory solution. It is therefore intended to be a dynamic tool that should be moulded and updated throughout the process. The number of scenarios that can be evaluated with a well built optimisation model is endless.

- The mill should keep the optimisation model updated, even after implementation of the selected treatment network. This way, any future risks and changes to the water and effluent system may be evaluated and optimised using the model.

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Appendix A Tugela *WinGEMS*™ model report

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1 Introduction

The purpose of the WinGEMS Tugela Mill model is to attempt to characterise the various sources of effluent in the mill. Furthermore, the completed model may be used to model proposed process changes in order to predict the impact of such changes in the quantity and quality of the resulting effluent.

The purpose of this report is to summarise the results obtained with the model, but also to point out the limitations of the model. This report includes the amended model results. as well as a new paper machine section.

2 Overview of the Model

The model was set up in different levels of detail. Figure 1 shows the overall Mill layout, including water and steam distribution and effluent lines. Each block contains a more detailed model of the particular part of the mill it represents. In some parts of the model, a third level is present, but this is mainly used to keep the diagrams tidy.

The key components included in the model are water, fibre, suspended solids, COD and sodium. Although many other components are present in the model, these components were not balanced throughout the mill. These components may, however, be incorporated fully into the model at a later stage.

The modelling of COD is difficult because COD is not a physical component, but a measure of the amount of oxygen required to fully oxidise all the contaminants contained in the stream. For the Tugela mill model, the COD was taken as approximately twice the amount of dissolved wood solids in each stream. This ratio gives a good correlation for the COD values that were measured throughout the mill.

To complete the model, several assumptions had to be made, especially in areas where laboratory data was incomplete. These assumptions are reported in each section, and have to be considered when evaluating the data.

The production data used for the simulation was obtained from various Mill Reports that are issued on a monthly basis by the Mill. The simulation was initially done using one month's average values. Although this is not ideal and a longer period would be preferable, the Mill had been running very variably during the previous six months, and therefore the data would be distorted if this period was used. Instead, one month was chosen in which the Mill operation was relatively steady.

Since the completion of the original model, several sampling programmes have been undertaken to clarify uncertain areas within the model. One of these programmes was an effluent flow measuring programme, which made data available that was previously unknown, such as the waste drain flow rate.

The simulation represents a steady state process rather than a dynamic process. This means that the reported data is only one average scenario, and that the real Mill conditions may be very different at any given moment. Storage tanks and similar process units are therefore not simulated. If a tank overflows in the simulation, it will always overflow, although in reality the tank may overflow sometimes, but draw empty at other times.

The following general colour conventions were used in the model:

Mill Water and Domestic Water
Condensate streams
Steam
General Pulp or Wood
Kraft Pulp
NSSC Pulp
Waste Pulp
Broke
Effluent
Paper Machine White Water

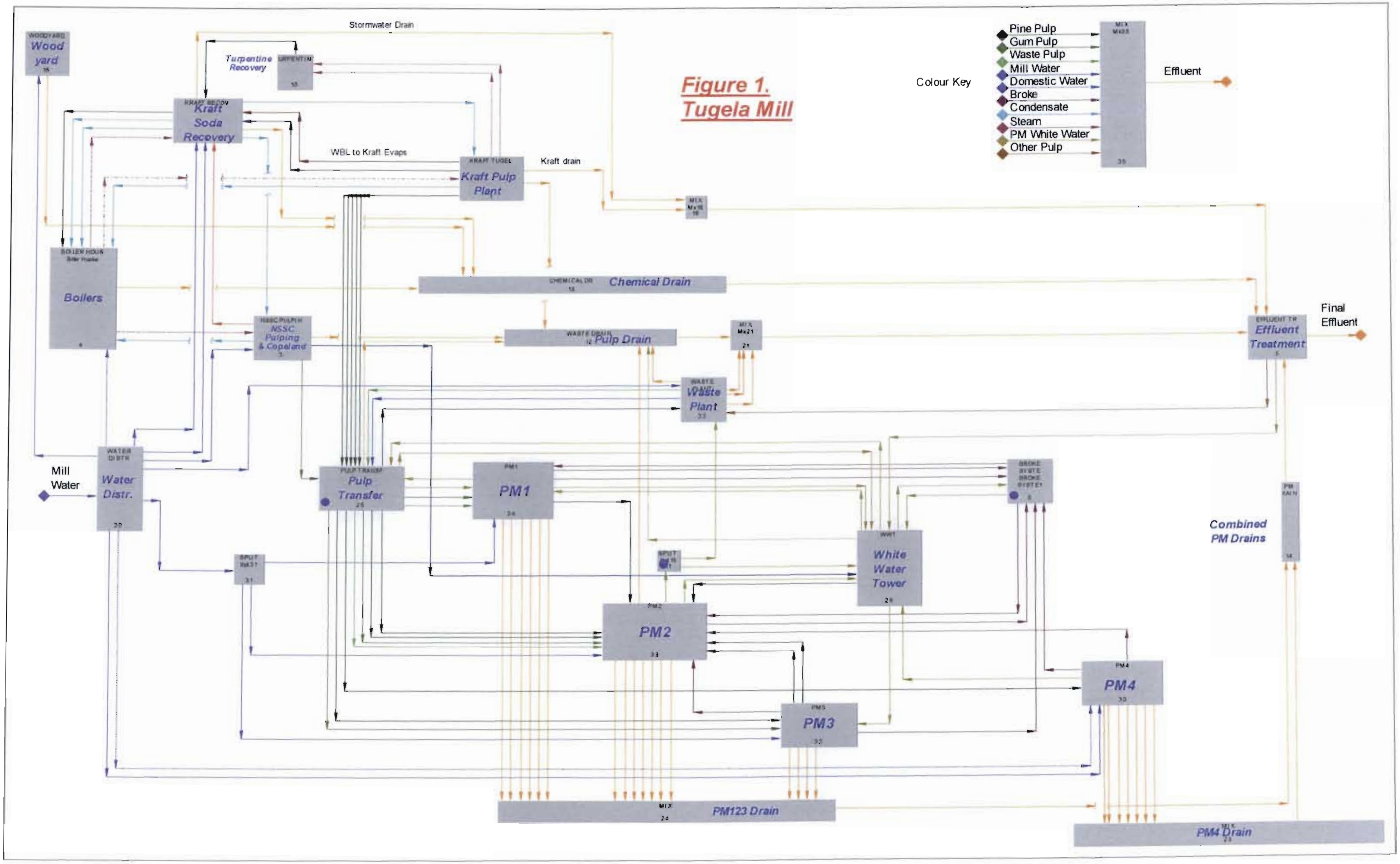


Figure 1. Tugela Mill

3 Kraft Pulping and Washing and Turpentine Recovery

3.1 Overview

The Kraft pulping section, shown in Figure 2, is the larger of the two pulp plants in Tugela Mill. It incorporates the Sunds and Swenson washers and the oxygen delignification section.

The washers use combined condensate from the Kraft evaporators to wash the sodium and dissolved wood solids from the pulp. This wash water is then taken back to the digester via the counter current pulp washing system. In order to remove the maximum sodium from the pulp, the Sunds lines and the delignification line has screw presses that press out excess liquor from the pulp. These effluents are sometimes recycled, but are mostly dumped into the Waste Drain, from where it leaves the Mill.

The vapours that escape from the digester contain organic components such as turpentine. The turpentine is recovered from the vapour stream in the turpentine recovery section, shown in Figure 3.

3.2 Assumptions

- The flow rates of the combined condensate used to wash on the Sunds and Swenson washers are not known. The wash flow tempo is set by measuring the free sodium content of the pulp exiting the washers. The flow rates had to be guessed by estimating the washing efficiency of the washers, and to wash to the measured average free sodium levels as reported by the plant's laboratory.

- After the post-O2-delig drum displacement washer, the pulp is either sent directly to pulp transfer, or to the screw presses. The exact split ratio of the pulp varies and is unknown, and therefore had to be estimated. This in turn had an effect on the amount of screw press water sent to the Waste drain. The screw press flow was measured during a sampling programme, and the average values were used in the model.

- The exact distribution of the Mill water in the system is unknown. Therefore, the mill water used was assumed to be gland seal water, and was sent into the process stream and to the drains.

- The oxygen delignification section is presented as if delignification takes place 100% of the time. In reality this is not the case, as pulp is always sent through the delignification line, but delignification does not always take place (chemicals are not always added. The SWL addition for the month was obtained from the plant's stock sheets and divided by the number of days to obtain the average daily chemical addition.

- The steam consumption and condensate return figures were obtained from the monthly steam balance and the water consumption was taken from the monthly water distribution figures.

- The production figures were obtained from the Kraft plant's monthly statistical report. and are summarised in Table 1.

Table 1. Kraft digester cooking parameters

Parameter		Value
Pulp Yield in Digester	%	51.78
Wood Moisture	%	54
SWL EA charge on Wood	% as Na_2O	13.2
SWL EA	g/l as Na_2O	96.5

3.3 Summary of results

Table 2 summarises the main streams entering and exiting the Kraft pulping section.

Table 2. Main Inflow and Outflow Streams of the Kraft Pulp Plant

	Stream Description	Flow (l/min)	Solids (%)	COD (ppm)	Na (ppm)
Inlet Streams	Wood Chips to Digesters	960 ODtpd	46	-	-
	SWL to Digester	950		-	10.15 %
	Combined Condensate to Washers	3700	-	1160	72
	Total Steam in	785 tpd	-	-	-
	SWL to O_2 Delig	27	-	-	10.15 %
	Mill Water to Plant	990	-	50	41
Outlet Streams	Sunds Pulp	180 ODtpd	18	6460	13.6 kg Na/t pulp
	Swenson Pulp	40 ODtpd	16	4340	10 kg Na/t pulp
	Delig. Pulp from Screw Press	160 ODtpd	17	3060	4.4 kg Na/t pulp
	Delig. Pulp to HD Chest	108 ODtpd	12	4900	8.4 kg Na/t pulp
	WBL to Recovery	3840	-	14.5 %	2.6 %
	Vapour to Turpentine Recovery	309 tpd	-	-	-
	Condensate return to Boilers	570 tpd	-	-	-
	Effluent to Waste Drain	1133	2411 ppm	3786	675
	Effluent to Kraft Drain	2.5	-	1783 0	4282

3.4 Conclusion

The Kraft pulp plant model calculates the main pulp flows and chemical dosages. As the pulp plant is the biggest 'user' and 'producer' of sodium, the sources and destinations of sodium in this section is very important. By using the correct chemical charges in both the digester and O_2 delignification sections, and washing to a known sodium content in the pulp, the sodium balance can be completed. The main problem encountered in the simulation is the lack of knowledge of the amounts of water and condensate that is used in the plant. This, in turn reduces the confidence level in the effluents produced in the plant.

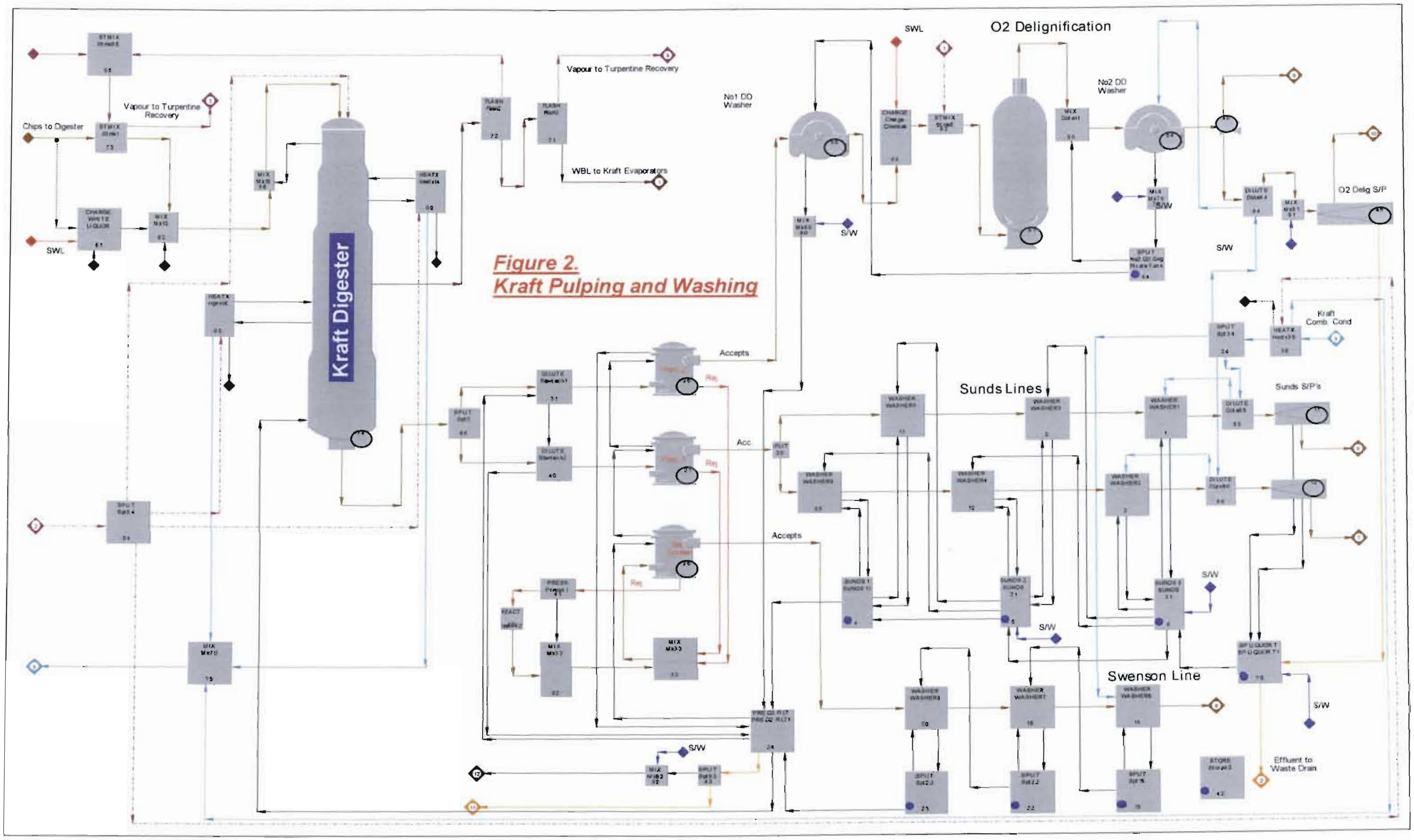
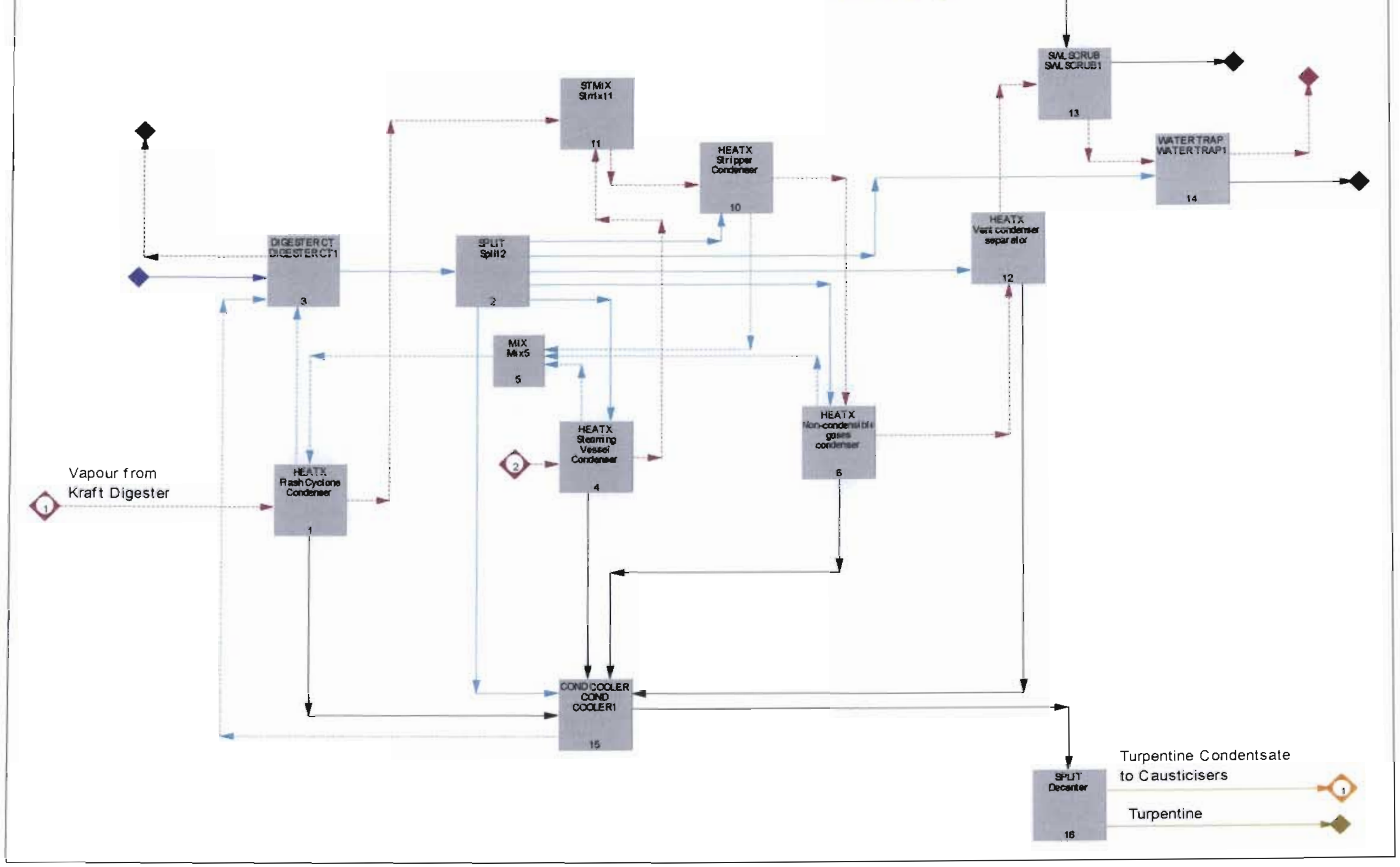


Figure 2.
Kraft Pulping and Washing

Figure 3. Turpentine Recovery



4 Kraft Soda Recovery

4.1 Overview

The soda recovery section comprises the Kraft evaporators, the Soda Recovery Furnaces (SRF), the causticising section and the lime kilns, and is shown in figures 4a, 4b and 4c. The recovery section forms an integral part of the overall Mill, as it recovers spent cooking chemicals to produce fresh SWL for chip cooking. A secondary function of the recovery section is the generation of HP steam in the furnaces. Furthermore, the condensate produced by the Kraft evaporators is used as wash water for the Kraft pulp washers and on the NSSC belt filter (see chapters on Kraft Pulping and NSSC Pulping).

4.2 Assumptions

- As mentioned in the chapter on Kraft Pulping, the amount of condensate used on the washers is not known. Furthermore, no condensate flows from the combined condensate tank are measured. As the Kraft and NSSC plants use more condensate than is produced by the evaporators, the combined condensate is made up with evaporator cooling tower water, of which the amount is also unknown. These values were therefore estimated.

- The exact distribution of the Mill water and Domestic water in the system is unknown. Therefore, all the water that was not used for cooling water or wash water on the mud washers, was assumed to be gland seal water, and was sent to the chemical drain. It was also assumed that there is some spillage of black liquor in the plant, which also goes to the chemical drain. The limekilns water usage was estimated, as the quantity is unknown.

- The limekiln effluent volume and concentration are assumed values. This is because the exact nature and origin of the effluent is not known. The lime kiln effluent goes to the storm water drain.

- The wash flow rates on the mud washers are not known, as washing is done to achieve a specific mud TA value. Therefore, the model assumed a washing efficiency and back calculated the required wash flow rate to achieve the specified mud TA values. Although various condensates as well as mill water are used to wash on the mud filters, the exact ratios are unknown and had to be estimated.

- The wash flow rates on the drum washers before the limekilns are unknown and had to be estimated.

- The steam consumption and condensate return figures were obtained from the monthly steam balance. In the model, the steam generation section of the furnaces is incorporated in the Boilers section and therefore only the chemical recovery part is shown in this section.

- The production data for the recovery plant was obtained from the Recovery section cost reports, as well as various logsheets. The Mill Laboratory monthly report was also used as a source of data.

4.3 Summary of results

Table 3 shows the main operating parameters used in the recovery section model

Table 3. Operating parameters of the recovery section

Parameter		Value
WBL solids entering evaporators	%	18
SBL solids exiting evaporators	%	50
HBL solids entering furnace	%	62-63
G/L TA	g/l as Na_2O	127
SWL Causticising Efficiency	%	83
SWL AA	g/l as Na_2O	113
WWL AA	g/l as Na_2O	22
Mud TA	g/l as Na_2O	<6

Table 4 summarises the main streams entering and exiting the Recovery section.

Table 4. Main Inflow and Outflow Streams of the Recovery section

	Stream Description	Flow (l/min)	TDS (%)	COD (ppm)	Na (ppm)
Inlet Streams	WBL from digester	3840	13.5	14.5 %	2.6 %
	Total Steam entering plant	1556 tpd	-	-	-
	Total Mill water to plant	1300	-	50	41
	Total Domestic water to plant	1460	-	50	41
Outlet Streams	Total condensate return to Boilers	1068 tpd	-	-	-
	Comb. Condensate to Kraft	3700	-	1150	65
	Comb. Condensate to NSSC	400	-	1150	65
	Effluent to chemical drain	1470	-	720	301
	Effluent from Lime kilns	54	-	-	350
	SWL produced	1070	-	-	9.09 %

4.4 Conclusion

The soda recovery model is very solid on the chemical recovery part, but unfortunately lacks solid data, especially water consumption and distribution data, to characterise the effluents with certainty.

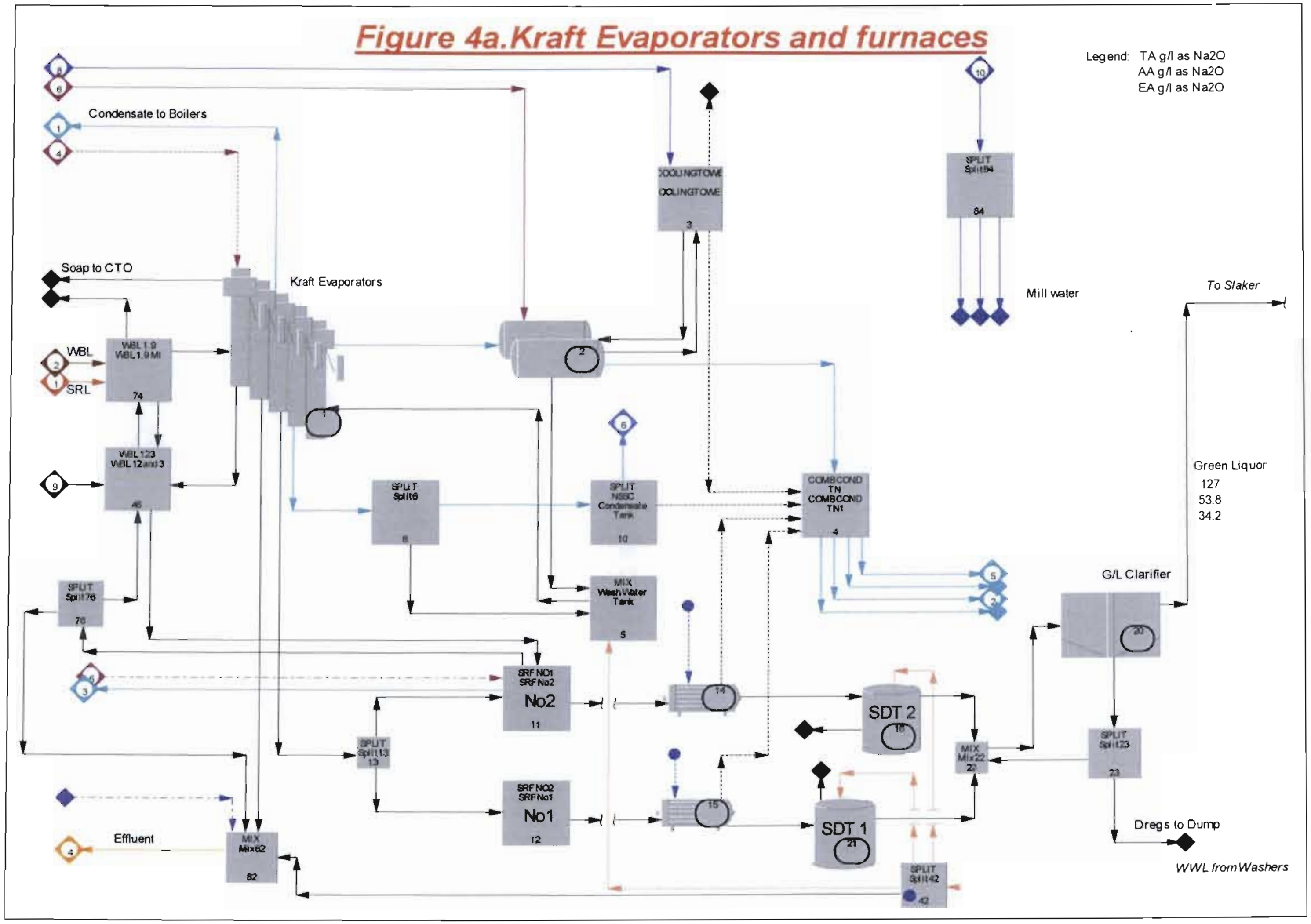
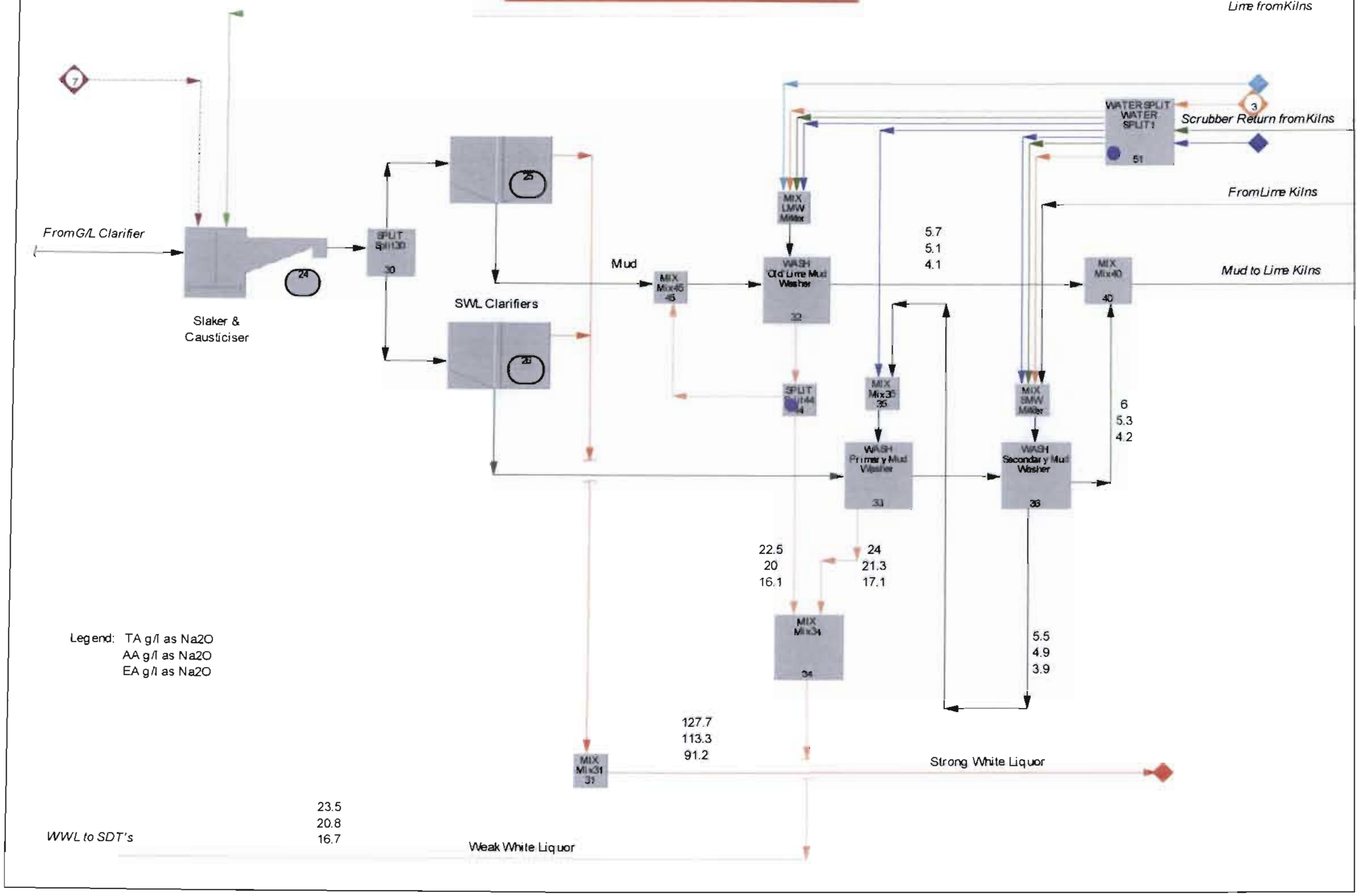


Figure 4a.Kraft Evaporators and furnaces
Legend: TA g/l as Na2O
AA g/l as Na2O
EA g/l as Na2O
Condensate to Boilers
Soap to CTO
Kraft Evaporators
WBL
SRL
Mill water
To Slaker
Green Liquor
127
53.8
34.2
G/L Clarifier
No2
No1
SDT 2
SDT 1
Effluent
Dregs to Dump
WWL from Washers

Figure 4b. Causticisers



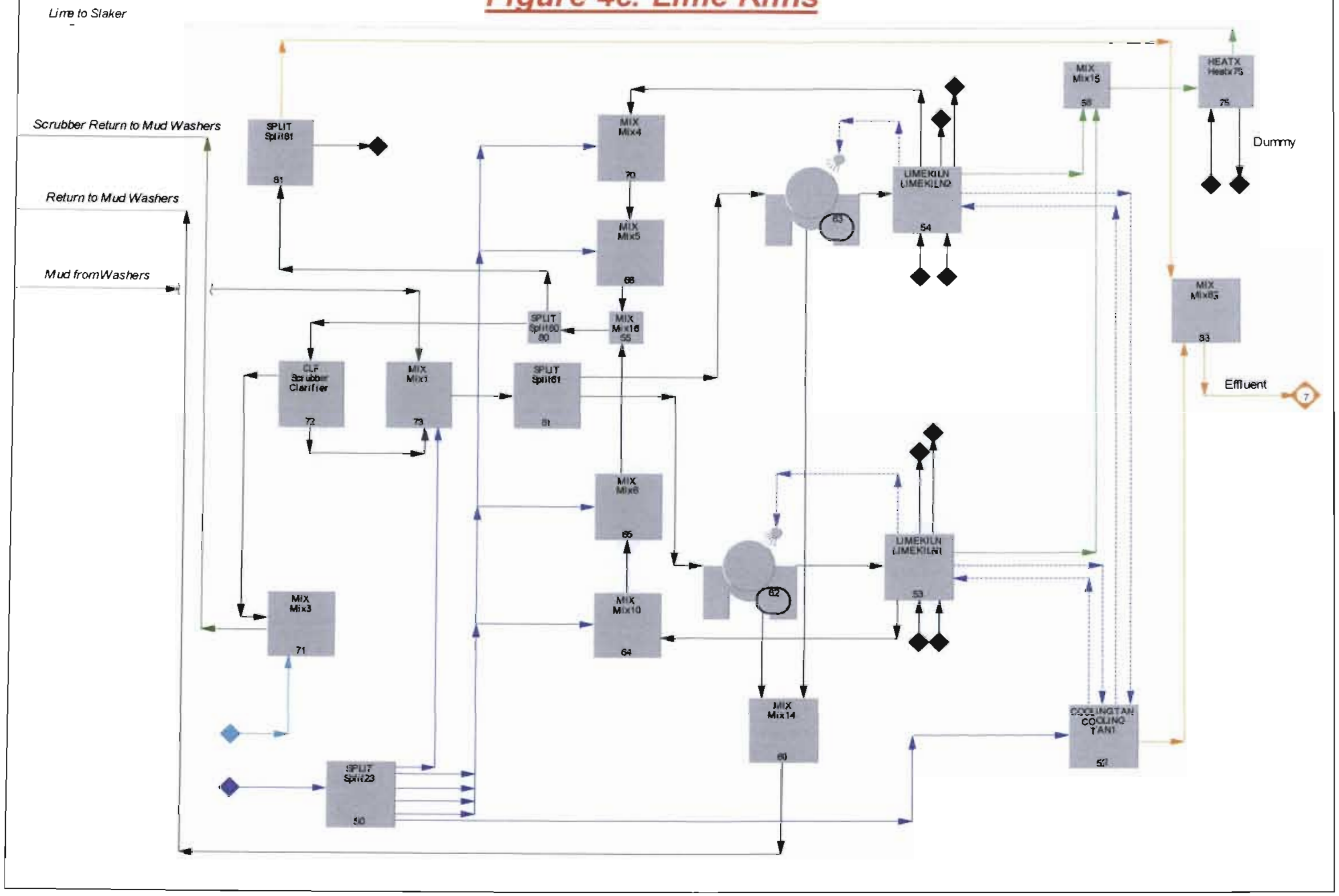


Figure 4c. Lime Kilns

5 NSSC Pulping and Copeland

5.1 Overview

The NSSC pulp plant and Copeland layout are shown in Figures 5a and 5b. The NSSC pulping section is smaller than the Kraft section and uses different cooking chemicals to digest the wood. Washing of the pulp is done with a belt filter, which uses a combination of Kraft condensate, NSSC condensate and hot mill water as wash water. Washing on the belt filter is done counter current, and the wash liquor is taken back to the digester. From the digester the spent cooking liquor, called weak red liquor (WRL), is sent to the Copeland recovery area, where the cooking chemicals are recovered as Na_2SO_4, which is sold. The NSSC system is therefore not a closed system like the Kraft system, but has sodium salts as a product.

5.2 Assumptions

- The mill water system in the NSSC plant is complicated by the fact that a lot of the water is used for cooling and then sent back to the water tower and the paper machines. The rest of the water is used for sealing water, which is assumed to end up in the Merensky sump, from where it is either recovered to the NSSC dilution tank, or overflows to the Copeland recovery sumps. An amount of mill water is taken to the gum repulper. This is taken as the excess water that is not used as cooling water or seal water in the NSSC plant.

- The amount of Kraft condensate, NSSC condensate and hot water that is used as wash water on the belt filter is not measured. The exact flow rates of each washing stage are also not measured, but the pulp is washed to a certain level of free sodium in the exiting pulp. Using the average free sodium values and estimated washing efficiencies, the flow rates of the wash water were estimated. The amount of Kraft condensate used was the taken as the amount of water required to make up the wash flows.

- The steam consumption and condensate return figures were obtained from the monthly steam balance and the water consumption was taken from the monthly water distribution figures.

- The production figures were obtained from the NSSC plant's monthly statistical report, and are summarised in Table 5.

Table 5. NSSC and Copeland operating parameters

Parameter		Value
Pulp Yield in Digester	%	77
Wood Moisture	%	34.7
Cooking liquor charge on Wood	% as Na_2SO_3	5.5
Cooking liquor concentration	g/l as Na_2SO_3	204.3
Buffer liquor charge on Wood	% as Na_2O	2.3
Buffer liquor strength	g/l as Na_2O	95.3
WRL solids entering evaporators	%	9.5
SRL solids exiting evaporators	%	19.4
HRL solids entering furnace	%	32.2
Na_2SO_4 in Copeland product	%	62.4

5.3 Summary of results

Table 6 summarises the main streams entering and exiting the NSSC and Copeland section.

Table 6. Main Inflow and Outflow Streams of the NSSC plant

	Stream Description	Flow (l/min)	Solids (%)	COD (ppm)	Na (ppm)
Inlet Streams	Wood chips to digester	353 ODtpd	65.3	-	-
	Cooking liquor to digester	67	-	-	204.3 g/l as Na2SO3
	Buffer liquor to digester	63	-	-	6.4 %
	Total Steam to NSSC	514 tpd	-	-	-
	Total Mill Water to NSSC	3055	-	50	41
	Kraft condensate to NSSC	400		1150	65
Internal Streams	WRL from digester to evaporators	680	-	14.5 %	1.97 %
Outlet Streams	Pulp from belt filter	272 ODtpd	20	8500	8.95 kg Na/t pulp
	Hot water to Paper Machines	1527	-	50	41
	Total condensate return to Boilers	220 tpd	-	-	-
	SRL to Kraft furnaces	85	-	23.6 %	3.2 %
	SRL to Tall Oil plant	2	-	23.6 %	3.2 %
	Effluent to Waste Drain	810	-	1000	71

5.4 Conclusion

The NSSC and Copeland plant is complicated by the complexity of its water system and the fact that the flow rates of the various contributing water and condensate sources are not known. Therefore, an area where the model may be improved with better data would be to know the exact contribution of each condensate stream used as wash water on the belt filter.

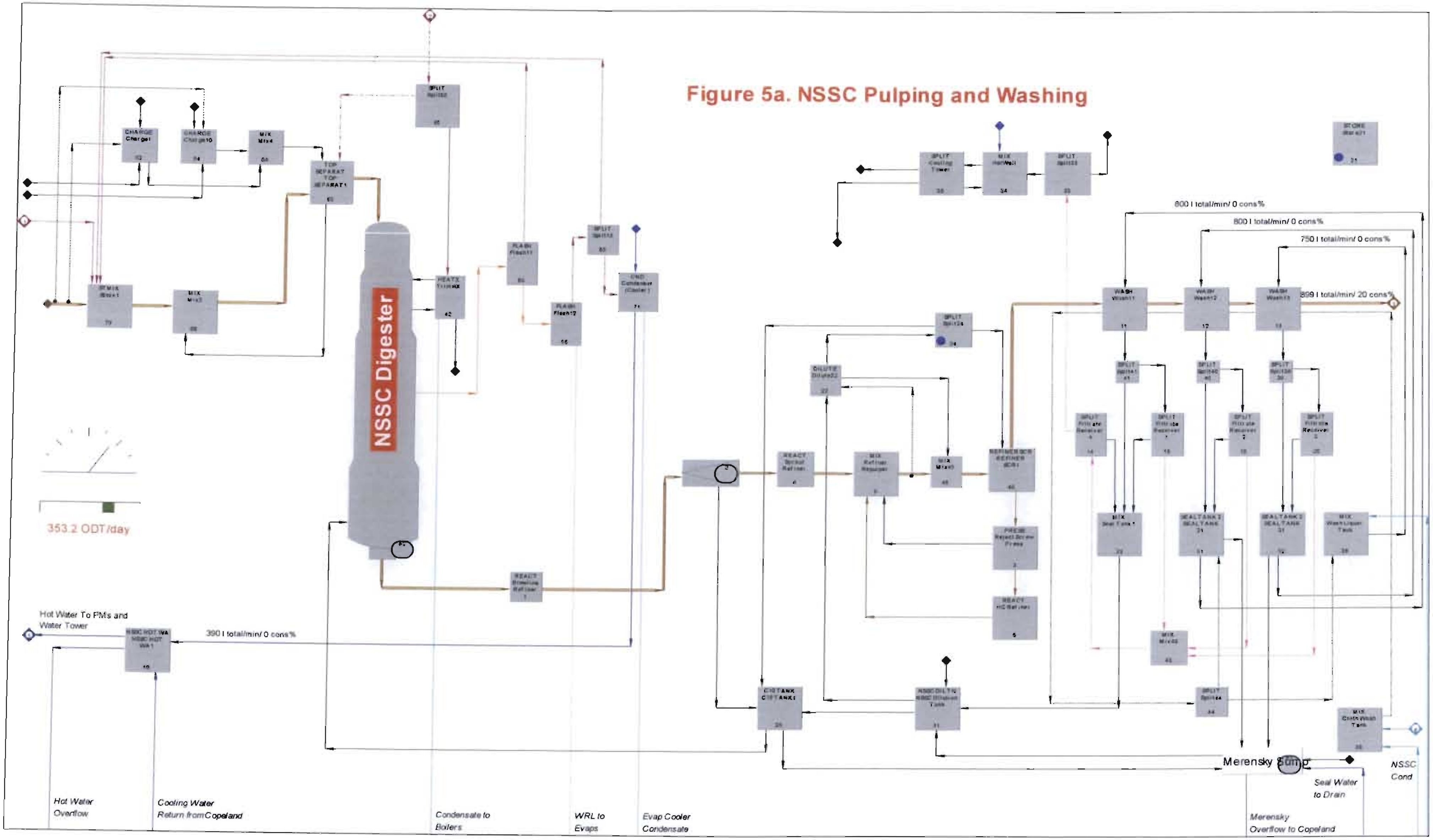


Figure 5a. NSSC Pulping and Washing

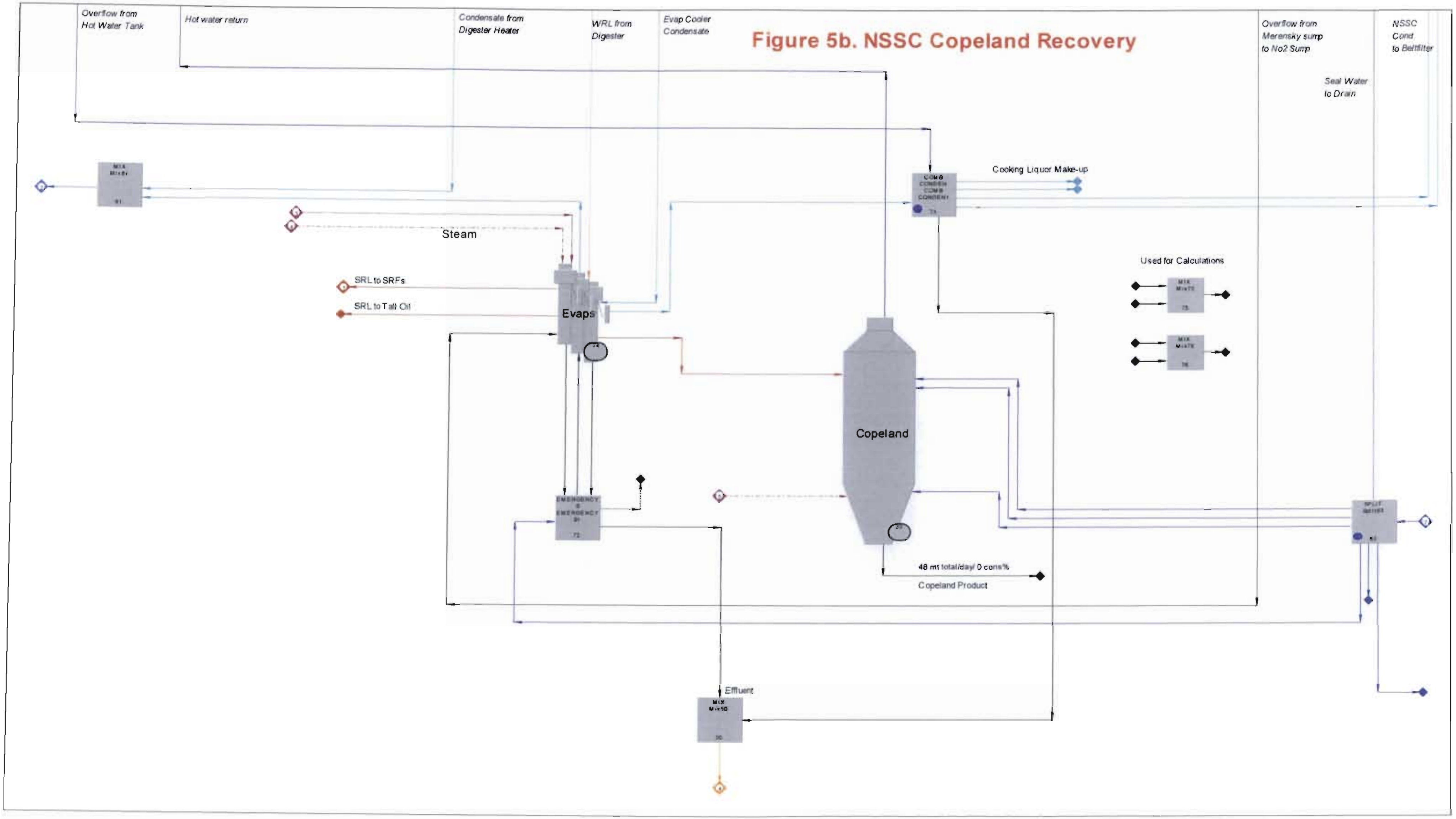


Figure 5b. NSSC Copeland Recovery
Overflow from Hot Water Tank
Hot water return
Condensate from Digester Heater
WRL from Digester
Evap Cooler Condensate
Overflow from Merensky sump to No2 Sump
NSSC Cond. to Beltfilter
Seal Water to Drain
Cooking Liquor Make-up
Steam
SRL to SRFs
SRL to Tall Oil
Evaps
Used for Calculations
Copeland
48 mt total/day/ 0 cons%
Copeland Product
Effluent

6 Waste Plant

6.1 Overview

The waste plant flowsheet is shown in figure 6. The waste plant produces waste pulp by repulping recycled bales of paper and screening the pulp to ensure that the pulp is of acceptable quality. The water that is used for dilution throughout the plant is water that is recovered from the waste thickeners and make-up water from the white water tower.

A portion of the underflow fibre from Clarifier 1 is recycled to the waste plant.

6.2 Assumptions

- The mill water that is used in the waste plant is used on the thickener sprays and as sealing water. The sealing water is assumed to go to the waste drain, after picking up some suspended solids from the waste plant floor area.

- The water consumption was obtained from the monthly water distribution figures.

- The production figures were obtained from the Waste Plant's monthly production figures.

6.3 Summary of results

Table 7 summarises the main streams entering and exiting the Waste plant.

Table 7. Main Inflow and Outflow Streams of the Waste Plant

	Stream Description	Flow (l/min)	Cons. (%)
Inlet Streams	Waste bales to repulper	185 Odtpd	90
	Return pulp from Clarifier 1	17.5 Odtpd	2
	Total Mill water to plant	1530	-
	Total white water usage in plant	6920	-
Outlet Streams	Waste pulp to Pulp Transfer	192 ODtpd	10
	Effluent from hydrasieve	648	0.37
	Other effluent	1230	-

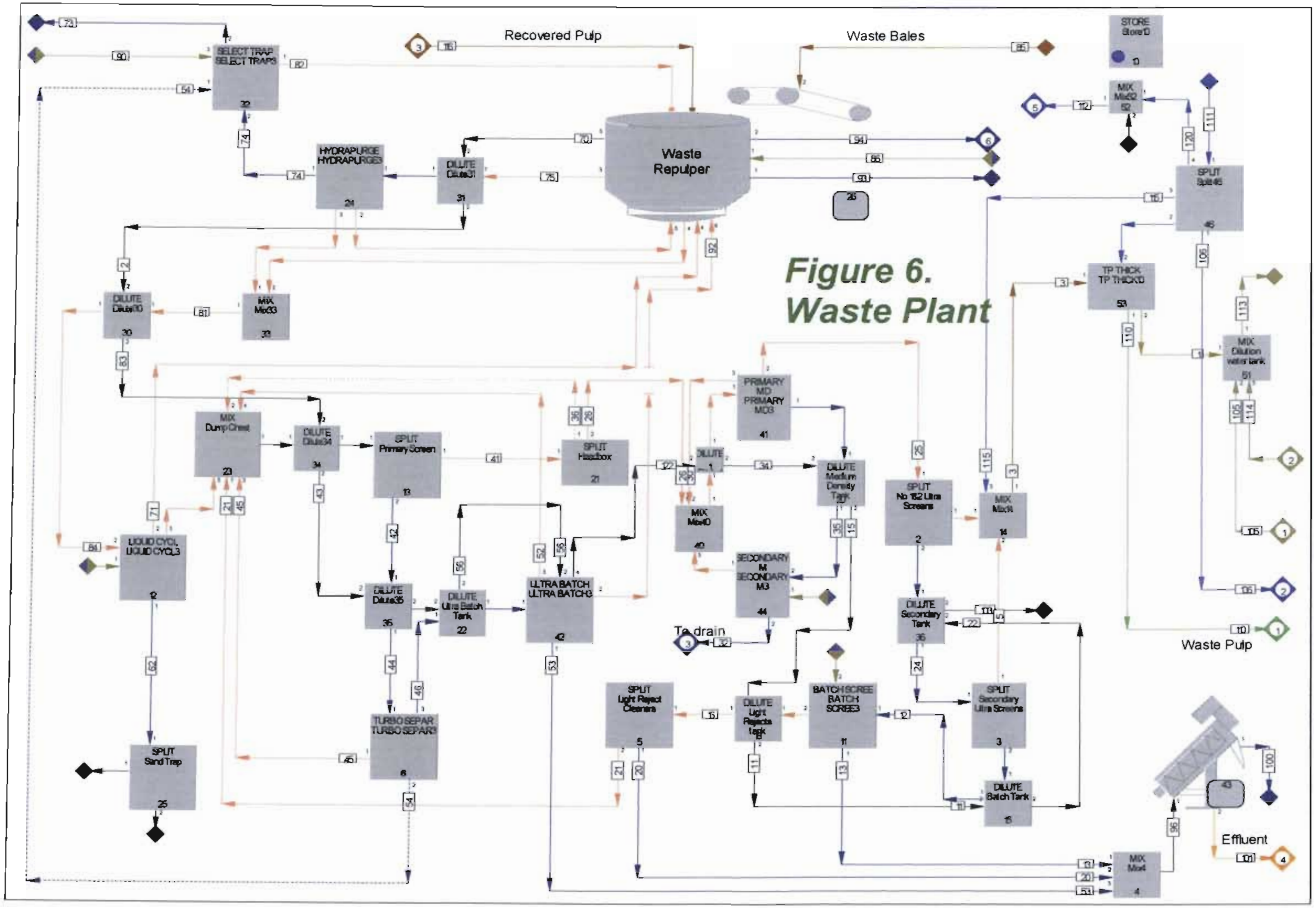


Figure 6. Waste Plant

7 Pulp Transfer and Paper Machines

7.1 Overview

The pulp transfer system forms the link between the pulping plants and the paper machines. Pulp from the pulp plants is diluted and stored in high density chests. ready for use by the paper machines. The paper machines remove most of the water that was added in the pulp transfer system, and returns it to the white water tower, ready for re-use as dilution water.

The pulp transfer system is shown in figure 7, and the paper machine layouts are shown in figures 8, 9, 10 and 11.

7.2 Assumptions

- The white water tower has a make up of hot water from the NSSC plant. Some of the hot water is also taken to the paper machines, but in this simulation, the whole amount is taken to the water tower.

- The flows entering and exiting the water tower were measured by C. Paxton and X. Khosa. Where possible, these figures were used to estimate the white water returns to the water tower. In some instances, however, pump specifications were used to estimate the flow to the water tower.

- An overflow from the water tower is reported by the model. This is an estimated value to account for overflows from the water tower, repulpers and high density chest in the pulp transfer section. This water overflows into the waste drain.

- Water tower water is also used to make up the waste plant water supply.

- The preliminary water and fibre balances over the paper machines were done by C. Paxton. These balances included the intermediate consistencies within the paper machines as well as the wire, couch pit and press consistencies. The model was built around these basic water and fibre balances.

- The cleaners balances for all the paper machines were done by C. Paxton and X. Khosa and incorporated in the model.

- Although PM2's and PM4's showers and sprays water consumption are known, PM1 and PM3 have flows that are unknown and therefore had to be estimated. These estimates were made by using figures quoted on P&ID's, and with the input of the respective paper machine process engineers.

- PM2 and PM4 polydisc performance data was obtained from Tugela Mill memorandum DFPM2 and from R&D memorandum M2000/207 respectively.

- The broke balancing for the combined paper machines was done by assuming an average breaking frequency for each paper machine (obtained from individual paper machine production and downtime sheets). The model was then programmed to simulate breaks as if they were part of normal production. Therefore, an amount of pulp was taken off each paper machine as broke, which was then sent to the respective broke storage chests and used as broke intake on each paper machine.

  In this way, the total broke used and total broke produced were balanced for all the paper machines.

- The mill water usage figures reported in the monthly mill water distribution figures do not account for the total water required by the paper machines, nor does it produce the effluent volumes measured by the mill or the effluent sampling programme. Therefore, the total mill water usage for each paper machine was taken as the amount of water required for showers, vacuum seal water, gland seal water and other makeup water used in each paper machine model.

- The steam consumption and condensate return figures were obtained from the monthly steam balance.

- The paper machine production figures were obtained from the paper machines staff and the effluent data used was obtained from the effluent sampling programme as well as the mill laboratory.

7.3 Summary of results

Table 8 summarises the stock used by each machine, as well as the production figures for each machine.

Table 8. Production and Stock usage for each paper machine

	PM1	PM2	PM3	PM4
Gross Production (odtpd)	235	630	31	226
Nett Production (odtpd)	206	570	25	180
Pine	No	Yes	Yes	Yes
NSSC	Yes	Yes	Yes	No
Waste	Yes	Yes	No	No
Broke	Yes	Yes	Yes	Yes

For the purposes of this report, paper machines 1, 2 and 3 will be reported together, as these paper machines' water and effluent systems are interlinked.

Table 9 summarises the main streams entering and exiting Paper Machines 1, 2, and 3.

Table 9. Main Entering and Exiting Streams for Paper Machines 1,2&3

Stream Description	Flow		COD (ppm)	Na (ppm)	Cons (%)
Streams Entering section					
Pulp intake to Paper Machines 1,2&3	1046	odtpd	1200-2100	230-376	4
Mill Water to Paper Machines	24200	m^3/day	50	41	-
Total Steam used by Paper Machines	2389	tpd	-	-	-
Streams Exiting Section					
Gross Paper Produced	896	odtpd	-	-	92
Nett Paper Produced	800	odtpd	-	-	92
Effluent to PM Drain	26952	m^3/day	698	197	1118ppm
Condensate return to Boilers	1537	tpd	-	-	-

Table 10 summarises the main streams entering and exiting Paper Machine 4.

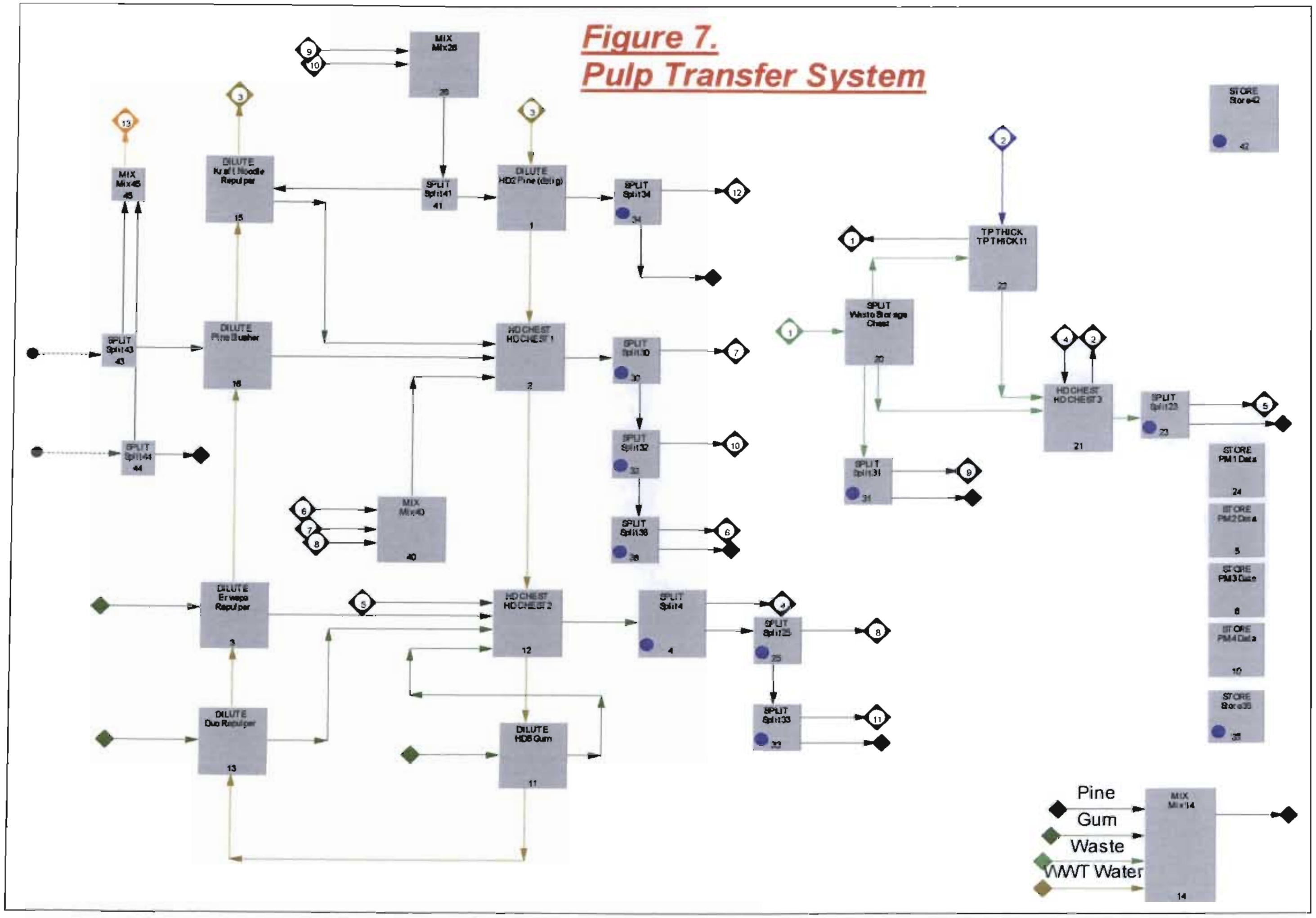
Table 10. Main Entering and Exiting Streams for Paper Machine 4

Stream Description	Flow		COD (ppm)	Na (ppm)	Cons (%)
Streams Entering section					
Pulp intake to Paper Machine 4	270	odtpd	1450	280	4
Total Water to Paper Machines	6309	m^3/day	50	41	-
Total Steam used by Paper Machines	813	tpd	-	-	-
Streams Exiting Section					
Gross Paper Produced	226	odtpd	-	-	92
Nett Paper Produced	180	odtpd	-	-	92
Effluent to PM Drain	4902	m^3/day	544	127	530 ppm
Condensate return to Boilers	247	tpd	-	-	-

7.4 Conclusion

Although the paper machine models with all the interconnected streams are quite complicated, the basic fibre and water balances still apply to this system. The total effluent produced by the paper machines correlate well with the actual measured values. Some of the paper machine effluent flows into the waste drain together with the water tower overflow and other contributing streams. The fact that the waste drain has been measured and correlates well with the model increases the confidence in the paper machine models.

Figure 7. Pulp Transfer System



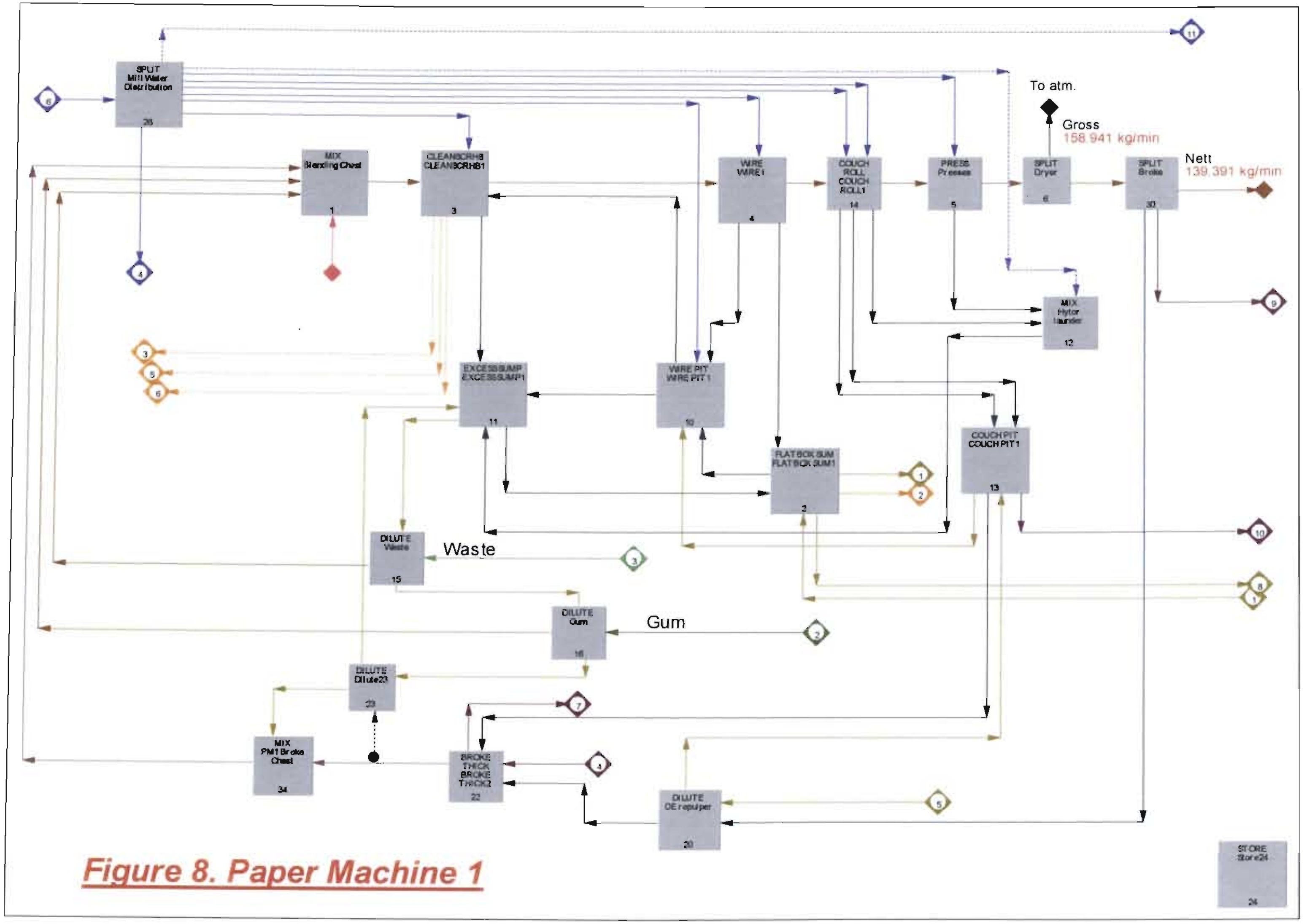
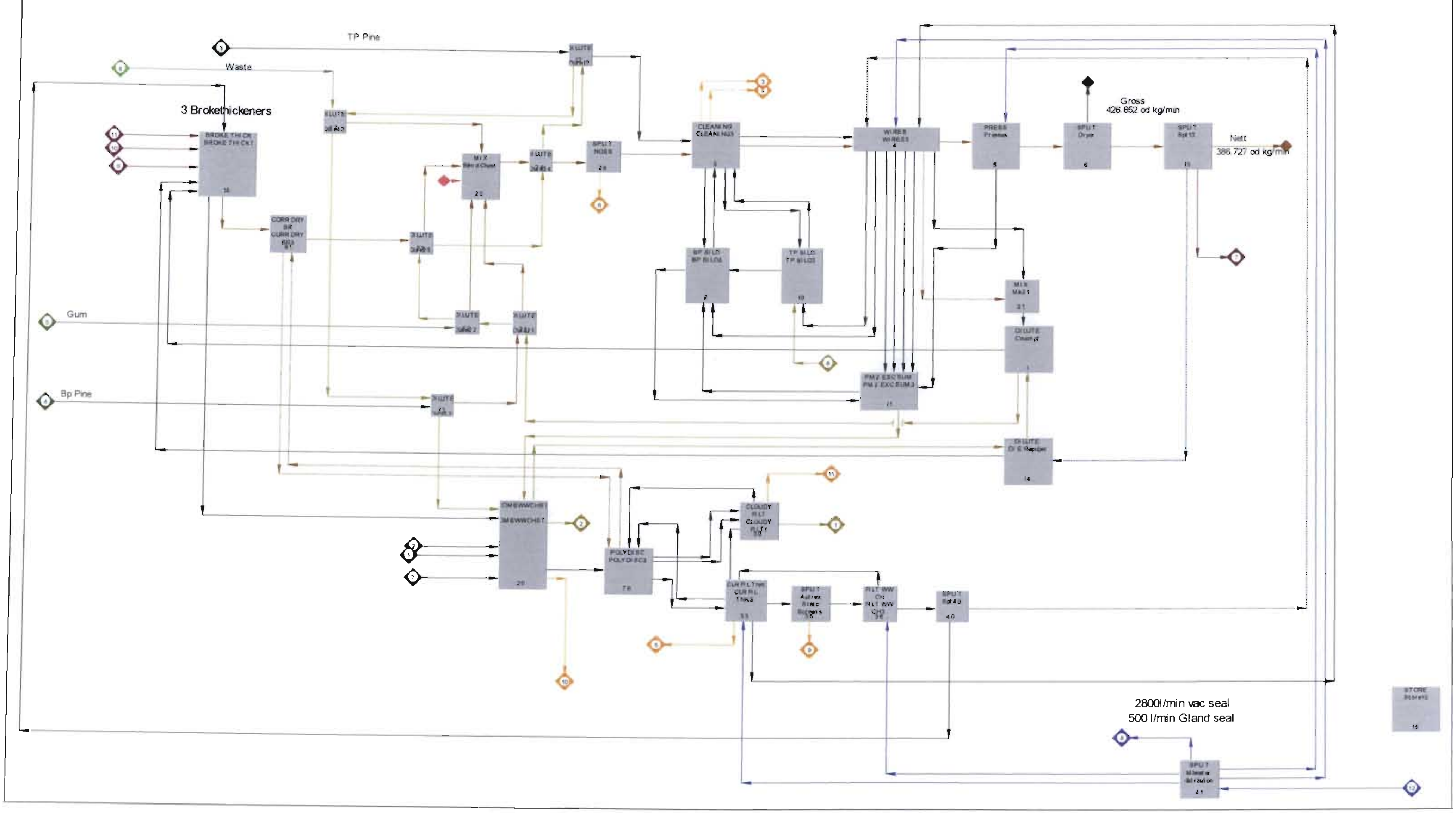


Figure 8. Paper Machine 1

Figure 9. Paper Machine 2



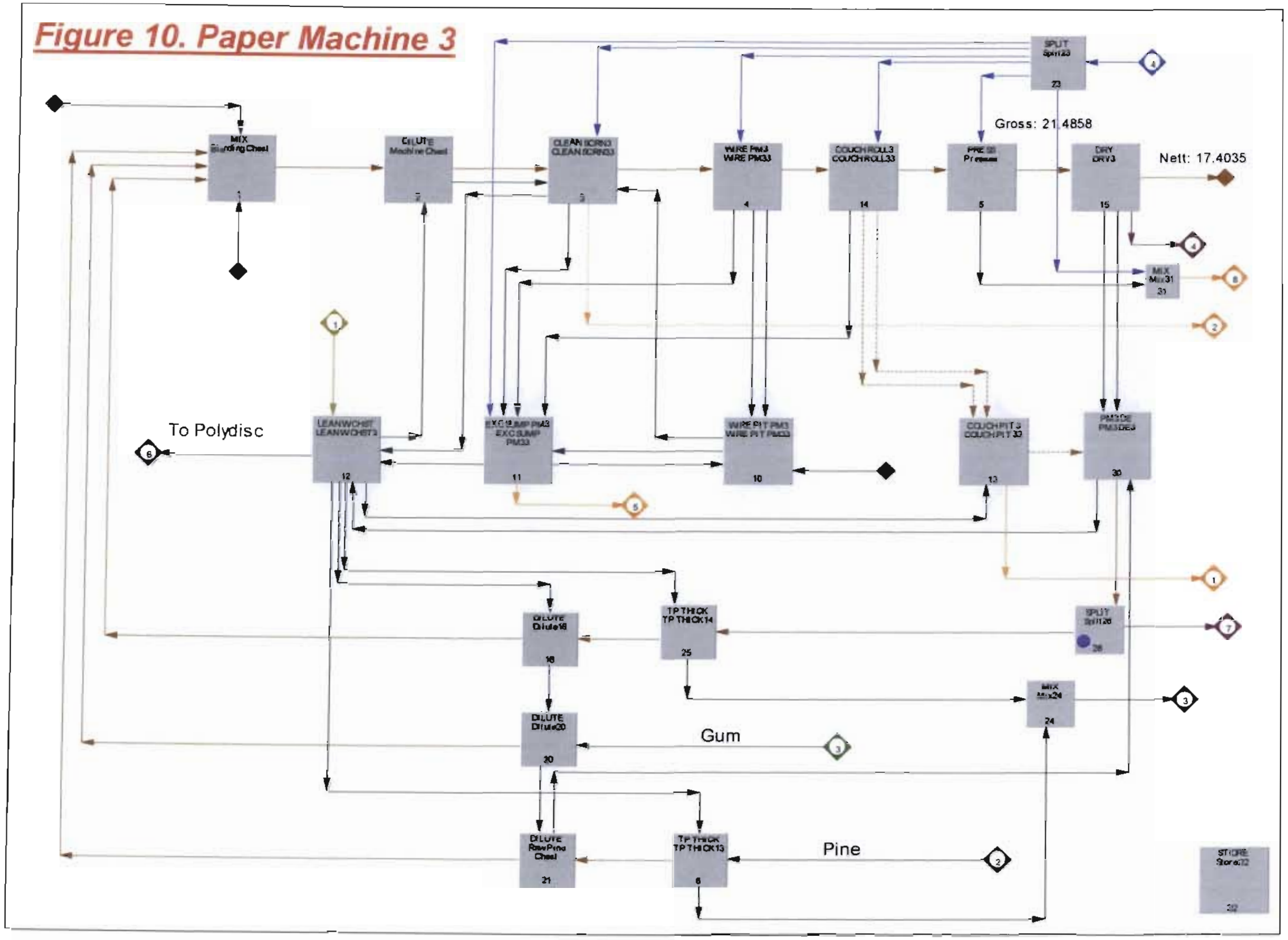


Figure 10. Paper Machine 3

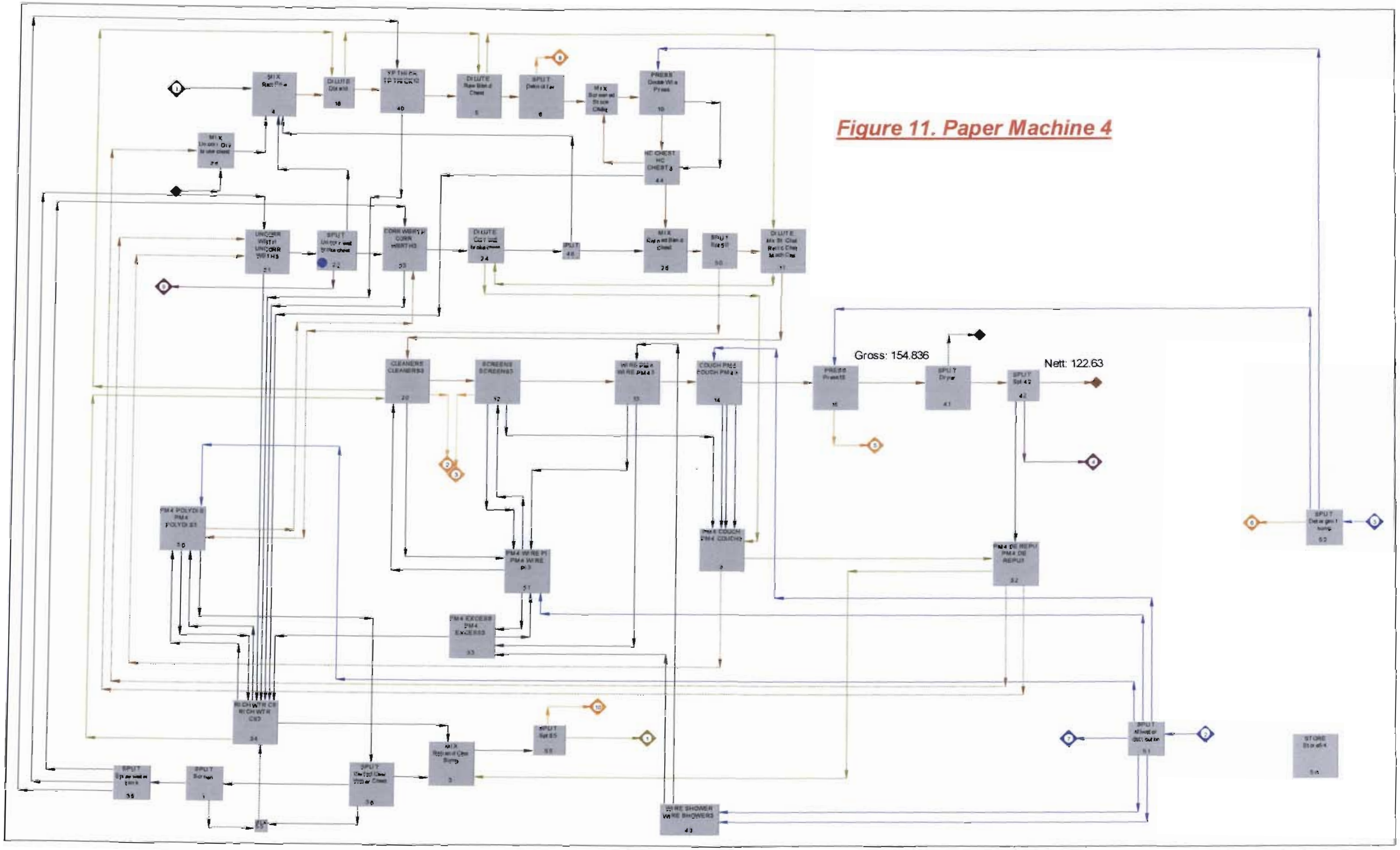


Figure 11. Paper Machine 4

8 Boilers and Steam Distribution

8.1 Overview

The boilers and steam distribution system is shown in figure 12. The boilers and the soda recovery furnaces generate steam using demineralised water and return condensate as boiler feed water. The high-pressure steam is converted to low pressure steam as required by the plants. The steam is also used to drive turbines, fans etc. in the plant, converting high-pressure steam into energy, low-pressure steam and condensate.

In the demineralisation plant. ion exchange units are used to remove the hardness from the boiler feed water. These ion exchange units have to be regenerated periodically. in order to ensure sufficient removal of the hardness in the water. The regeneration chemicals used are caustic soda and sulphuric acid. The regeneration effluent is therefore high in sodium and sulphates.

8.2 Assumptions

- It is assumed that all excess condensates are dumped to the chemical drain due to high conductivity. The amount of condensate that goes to effluent is calculated as follows:

  Total condensate to drain = (Demin Water from Demin plant + Condensate return - Total steam generated – Water used for de-superheating)

- Although this is a simplified calculation, it is used to prevent over-complication of the steam distribution system.

- Other sources of mill water and domestic water, as reported on the monthly water distribution figures, are also assumed to end up in the chemical drain, either as seal water, or water which is used for ash quenching.

- The steam distribution and condensate return figures were obtained from the monthly steam balance and the water consumption was taken from the monthly water distribution figures.

8.3 Summary of results

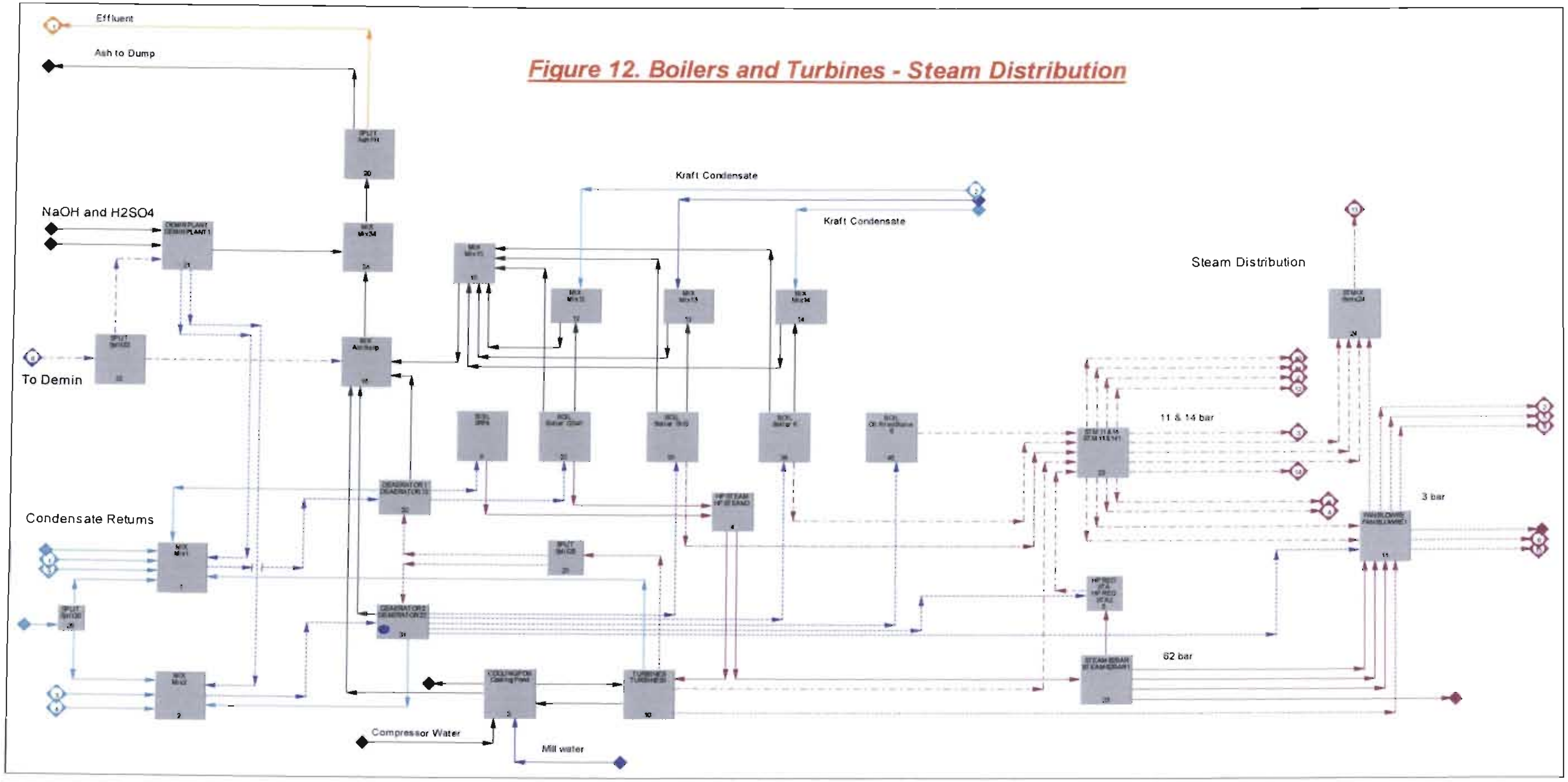
Table 11 summarises the main streams entering and exiting the boilers.

Table 11. Main Inflow and Outflow Streams of the Boilers

	Stream Description	Flow (l/min)		COD (ppm)	Na (ppm)	Solids (ppm)
Inlet Streams	Domestic water to Demin. Plant	3990		50	41	-
	Total Mill Water into plant	3510		50	41	-
	Total Condensate return to boilers (including turbines and de-aerators)	4505	tpd	-	-	-
Internal Streams	Regeneration Effluent	404		-	1733	-
Outlet Streams	Total steam generated by boilers	7120	tpd	-	-	-
	Total Effluent to drain	4937		404	215	1793

8.4 Conclusion

The boilers are a major source of effluent in the mill. The demineralisation plant regeneration effluent is a major source of sodium and sulphates in the chemical drain.


Effluent
Ash to Dump
Figure 12. Boilers and Turbines - Steam Distribution
Kraft Condensate
Kraft Condensate
NaOH and H2SO4
Steam Distribution
To Demin
11 & 14 bar
3 bar
Condensate Returns
62 bar
Compressor Water
Mill water

9 Effluent treatment

9.1 Overview

In the effluent treatment plant, the combined effluents are clarified and dumped in the river. This is done with two clarifiers. Figure 13 shows the flow configuration of the effluent treatment system.

In Clarifier 1, the paper machine effluents are clarified, and the underflow recovered to the waste plant. A portion of the clarified water is returned to the paper machines for reuse, while the rest of the clarifier overflow leaves the mill as final effluent. All the paper machine effluent that can not be accommodated in Clarifier 1 goes to Clarifier 1 bypass drain, which joins the chemical and waste drains.

The chemical and waste drains flow together at the junction, and the Clarifier 1 bypass drain joins the combined effluent a short way downstream of the junction. This combined effluent enters Clarifier 2, where the solids are allowed to settle. The Clarifier 2 sludge is sent through a belt press for de-watering, and the sludge is trucked away to a dumping site. The Clarifier 2 overflow leaves the mill as final effluent.

The emergency dams collect effluent that has an unacceptably high conductivity and cannot be allowed to pass directly through Clarifier 2. The contents of the emergency dams are bled back in small amounts into Clarifier 2. This way, the small amount of highly polluted effluent is diluted by a large volume of effluent.

9.2 Assumptions

- The flow and composition of the paper machine effluents are known. The Clarifier 2 overflow that goes to final effluent is measured, and the bypass drain flow is calculated (see above). Therefore, the amount of clarifier overflow that is returned to the paper machines can be calculated as follows:

  Clarifier 1 return to Water Tower = Total PM effluent – Clarifier 1 bypass – Clarifier 1 overflow to final effluent – clarifier underflow

- The flow of the bleed back stream from the emergency dams is unknown, and is therefore estimated. The Kraft and storm water drains are assumed to flow directly to the emergency dams, because of a high sodium content, although in reality it does sometimes flow directly into the Clarifier 2, depending on its conductivity.

- The effluent streams were measured during the sampling programme. The effluent system was balanced to match the measured data as closely as possible.

9.3 Summary of results

Figure 13 contains stream data for the streams entering and exiting the effluent treatment system. Table 12 summarises the most important streams entering and exiting effluent treatment section.

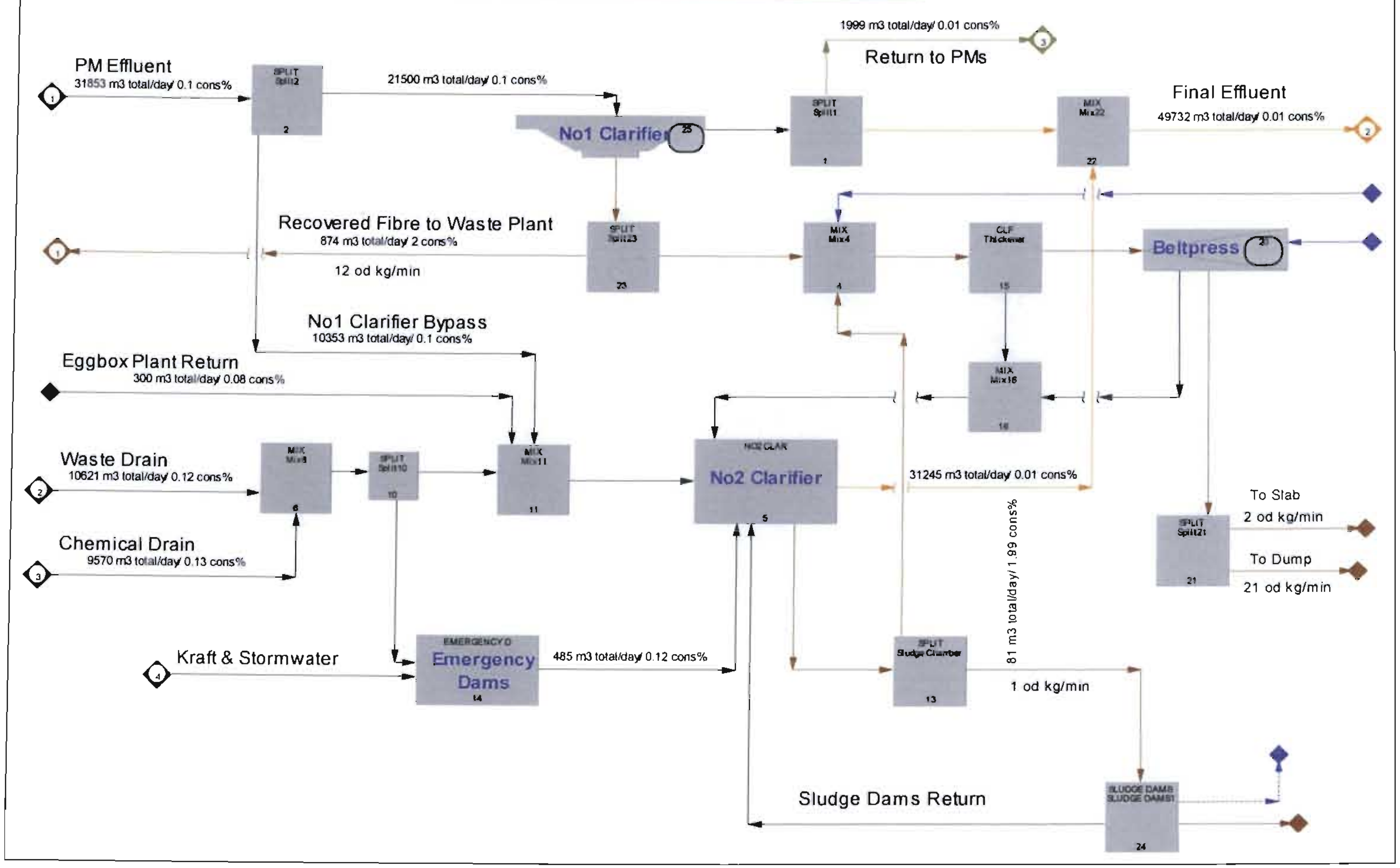
Table 12. Main Inflow and Outflow Streams of the Effluent system

	Stream Description	Flow (m^3/day)	Na (ppm)	COD (ppm)	Solids (ppm)
Inlet Streams	Paper machine effluent to Clarifier 1	31853	186	673	1027
	Total Waste drain	10620	250	1222	1205
	Chemical Drain	9570	227	464	1339
	Kraft and Storm water drain to emergency dams	56	517	760	1082
	Eggbox plant return water	300	200	1200	800
Internal Streams	Flow to Clarifier 1	21500	186	673	1027
	Underflow from Clarifier 1	20.3 ODtpd	186	673	2 %
	Clarifier 1 overflow to final effluent	18493	186	466	86
	Clarifier 2 overflow to final effluent	31244	220	636	132
	Clarifier 2 underflow	32.4 ODtpd	220	636	2%
	Clarifier 1 bypass drain flow	10353	186	673	1027
Outlet Streams	Clarifier 1 overflow return to paper machines	2000	186	466	86
	Clarifier 1 return sludge to Waste plant	17.5 ODtpd	186	-	2 %
	Belt press pulp to dump	30.8 ODtpd	167	606	20 %
	Final Effluent leaving mill	49732	207	573	115

9.4 Conclusion

In the previous version of this report, it was stated that the effluent system had too many unknown streams, and that the waste drain, an integral effluent stream, had to be monitored for flow in order to balance the effluents. This has since been done through a flow monitoring programme, and therefore the effluent system could be balanced using actual data.

Figure 13. Effluent Treatment



10 Sources of Information

The following sources were used for the building of the model.

- Tugela Mill Laboratory Monthly Report
- Kraft & NSSC Monthly Stock sheets
- Kraft & NSSC Monthly Statistical Report
- Kraft & NSSC daily logsheets
- Monthly Mill water distribution figures
- Monthly Mill steam distribution figures
- Soda Recovery section Monthly VP cost reports
- Soda Recovery logsheets
- Weekly Paper Machines fibre balances
- Waste plant production figures
- Tugela Mill Process and Instrumentation Diagrams
- Mansfield, M. (1999). *Effluent balance for Tugela Mill – Phase 1 of effluent project.* R&D M99/225.
- Flow and composition monitoring programmes.
- Verbal communications with staff from the various plants that were modelled.

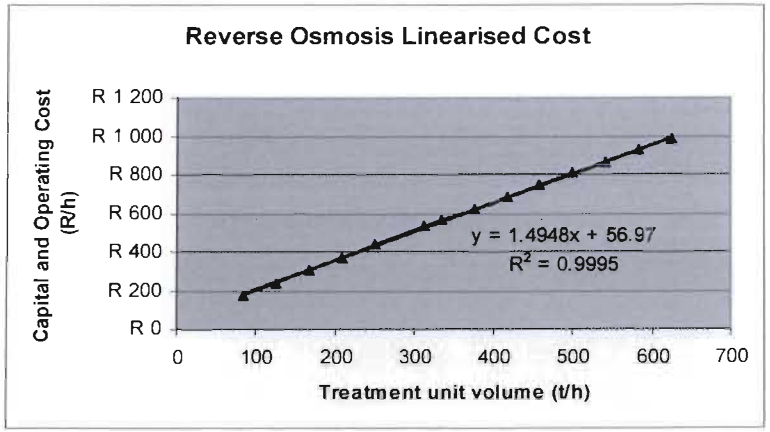
Appendix B Cost data for treatment units

Table B-1 Cost data for the Reverse Osmosis unit B-2
Table B-2 Cost data for the Activated sludge plants B-3
Table B-3 Cost data for the Dissolved Air Flotation unit B-4
Table B-4 Cost data for the Brine concentrator B-5
Table B-5 Cost data for the Sand filter B-6

Table B-1 Cost data for the Reverse Osmosis unit

Capital Cost	R 14 000 000
Size used as basis	7500 m^3/day
Rate	10%
Lifetime	20 years
Operating cost	R 1.10/m^3

Equation constants	R/t	R/h
	1.49	56.97

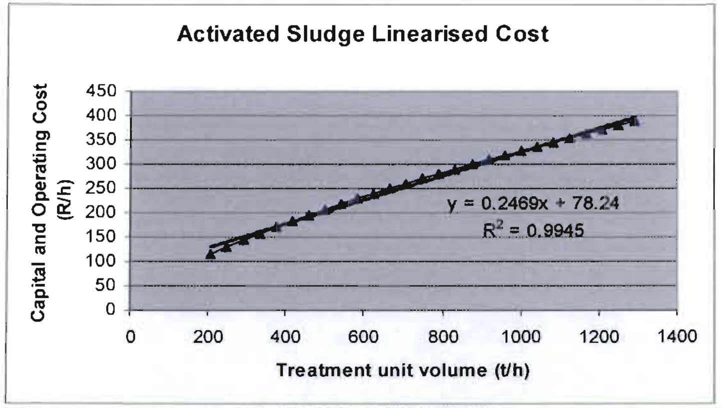


Volume treated (size, m^3/day)	Volume treated (size, m^3/h)	Capital cost	Capital unacost (R/y)	Operating cost (R/y)	Capital + Operating Cost (R/y)	Capital + Operating Cost (R/h)
2000	83	R 5 800 167	R 681 285	R 800 000	R 1 481 285	R 169
3000	125	R 7 600 369	R 892 737	R 1 200 000	R 2 092 737	R 239
4000	167	R 9 207 192	R 1 081 473	R 1 600 000	R 2 681 473	R 306
5000	208	R 10 684 000	R 1 254 939	R 2 000 000	R 3 254 939	R 372
6000	250	R 12 064 834	R 1 417 131	R 2 400 000	R 3 817 131	R 436
7500	313	R 14 000 000	R 1 644 435	R 3 000 000	R 4 644 435	R 530
8000	333	R 14 615 506	R 1 716 732	R 3 200 000	R 4 916 732	R 561
9000	375	R 15 809 405	R 1 856 967	R 3 600 000	R 5 456 967	R 623
10000	417	R 16 959 792	R 1 992 091	R 4 000 000	R 5 992 091	R 684
11000	458	R 18 072 393	R 2 122 776	R 4 400 000	R 6 522 776	R 745
12000	500	R 19 151 731	R 2 249 555	R 4 800 000	R 7 049 555	R 805
13000	542	R 20 201 460	R 2 372 856	R 5 200 000	R 7 572 856	R 864
14000	583	R 21 224 585	R 2 493 032	R 5 600 000	R 8 093 032	R 924
15000	625	R 22 223 615	R 2 610 377	R 6 000 000	R 8 610 377	R 983

Table B-2 Cost data for the Activated sludge plants

Capital Cost	R 27 000 000
Size used as basis	28 000 m^3/day
Rate	10%
Lifetime	20 years
Operating cost	R 0, R0.51/kg DWS

Equation constants	R/t	R/h
	0.25	**78.24**



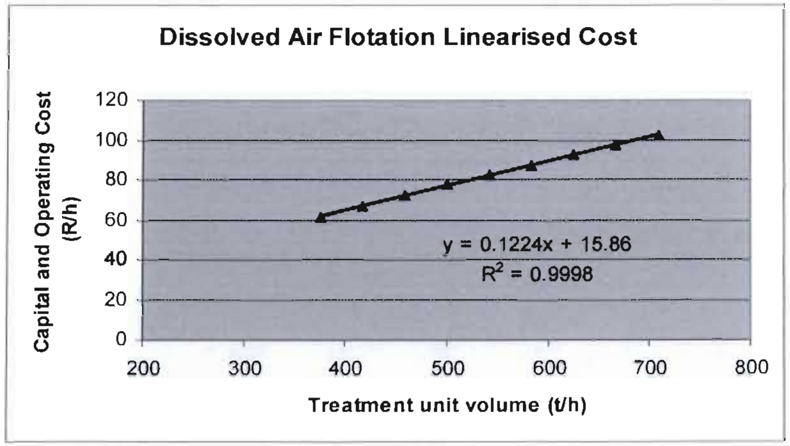
Volume treated (size, m^3/day)	Volume treated (size, m^3/h)	Capital cost	Capital unacost (R/y)	Operating cost (R/y)*	Capital + Operating Cost (R/y)	Capital + Operating Cost (R/h)
5000	208	R 8 561 931	R 1 005 681	-	R 1 005 681	R 115
6000	250	R 9 668 503	R 1 135 659	-	R 1 135 659	R 130
8000	333	R 11 712 557	R 1 375 753	-	R 1 375 753	R 157
10000	417	R 13 591 219	R 1 596 419	-	R 1 596 419	R 182
12000	500	R 15 347 792	R 1 802 746	-	R 1 802 746	R 206
14000	583	R 17 008 934	R 1 997 863	-	R 1 997 863	R 228
16000	667	R 18 592 526	R 2 183 871	-	R 2 183 871	R 249
18000	750	R 20 111 297	R 2 362 265	-	R 2 362 265	R 270
20000	833	R 21 574 715	R 2 534 158	-	R 2 534 158	R 289
22000	917	R 22 990 065	R 2 700 404	-	R 2 700 404	R 308
24000	1000	R 24 363 101	R 2 861 681	-	R 2 861 681	R 327
26000	1083	R 25 698 472	R 3 018 533	-	R 3 018 533	R 345
28000	1167	R 27 000 000	R 3 171 410	-	R 3 171 410	R 362
30000	1250	R 28 270 875	R 3 320 686	-	R 3 320 686	R 379
31000	1292	R 28 895 677	R 3 394 075	-	R 3 394 075	R 387

* Operating cost is zero, as the operating cost is expressed as R/kg DWS entering the plant

Table B-3 Cost data for the Dissolved Air Flotation unit

Capital Cost	R 4 000 000
Size used as basis	15 000 m^3/day
Rate	10%
Lifetime	20 years
Operating cost	R 0.062/m^3

Equation constants	R/t	R/h
	0.12	**15.86**

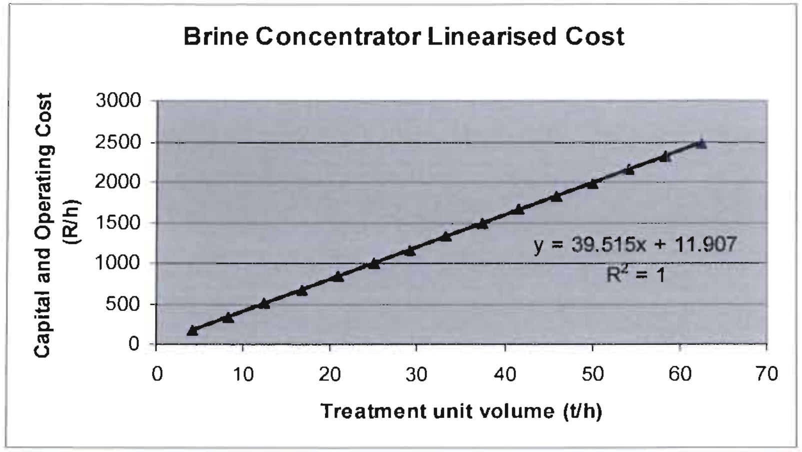


Volume treated (size, m^3/day)	Volume treated (size, m^3/h)	Capital cost	Capital unacost (R/y)	Operating cost (R/y)	Capital + Operating Cost (R/y)	Capital + Operating Cost (R/h)
9000	375	R 2 845 515	R 334 233	R 204 000	R 538 233	R 61
10000	417	R 3 052 571	R 358 554	R 226 667	R 585 221	R 67
11000	458	R 3 252 827	R 382 076	R 249 333	R 631 409	R 72
12000	500	R 3 447 096	R 404 895	R 272 000	R 676 895	R 77
13000	542	R 3 636 035	R 427 087	R 294 667	R 721 754	R 82
14000	583	R 3 820 186	R 448 718	R 317 333	R 766 051	R 87
15000	625	R 4 000 000	R 469 838	R 340 000	R 809 838	R 92
16000	667	R 4 175 859	R 490 495	R 362 667	R 853 161	R 97
17000	708	R 4 348 089	R 510 725	R 385 333	R 896 058	R 102

Table B-4 Cost data for the Brine concentrator

Capital Cost	R 4 000 000
Size used as basis	1 000 m^3/day
Rate	10%
Lifetime	20 years
Operating cost	R 38.54/m^3

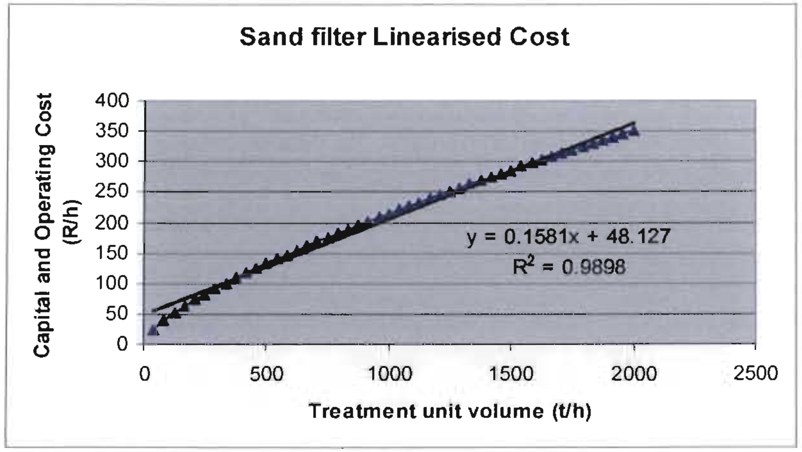
Equation constants	R/t	R/h
	39.52	11.91



Volume treated (size, m^3/day)	Volume treated (size, m^3/h)	Capital cost	Capital unacost (R/y)	Operating cost (R/y)	Capital + Operating Cost (R/y)	Capital + Operating Cost (R/h)
100	4.2	R 861 774	R 101 224	R 1 406 710	R 1 507 934	R 172
200	8.3	R 1 367 981	R 160 683	R 2 813 420	R 2 974 103	R 340
300	12.5	R 1 792 562	R 210 554	R 4 220 130	R 4 430 684	R 506
400	16.7	R 2 171 534	R 255 068	R 5 626 840	R 5 881 908	R 671
500	20.8	R 2 519 842	R 295 980	R 7 033 550	R 7 329 530	R 837
600	25.0	R 2 845 515	R 334 233	R 8 440 260	R 8 774 493	R 1 002
700	29.2	R 3 153 494	R 370 408	R 9 846 970	R 10 217 378	R 1 166
800	33.3	R 3 447 096	R 404 895	R 11 253 680	R 11 658 575	R 1 331
900	37.5	R 3 728 679	R 437 969	R 12 660 390	R 13 098 359	R 1 495
1000	41.7	R 4 000 000	R 469 838	R 14 067 100	R 14 536 938	R 1 659
1100	45.8	R 4 262 409	R 500 661	R 15 473 810	R 15 974 471	R 1 824
1200	50.0	R 4 516 973	R 530 562	R 16 880 520	R 17 411 082	R 1 988
1300	54.2	R 4 764 554	R 559 643	R 18 287 230	R 18 846 873	R 2 151
1400	58.3	R 5 005 860	R 587 986	R 19 693 940	R 20 281 926	R 2 315
1500	62.5	R 5 241 483	R 615 663	R 21 100 650	R 21 716 313	R 2 479

Table B-5 Cost data for the Sand filter

Capital Cost	R 16 000 000
Size used as basis	28 000 m^3/day
Rate	10%
Lifetime	20 years
Operating cost	R 0.02/m^3



Equation constants	R/t	R/h
	0.16	48.13

Volume treated (size, m^3/day)	Volume treated (size, m^3/h)	Capital cost	Capital unacost (R/y)	Operating cost (R/y)	Capital + Operating Cost (R/y)	Capital + Operating Cost (R/h)
1000	42	R 1 735 194	R 203 815	R 7 857	R 211 672	R 24
5000	208	R 5 073 737	R 595 959	R 39 286	R 635 245	R 73
10000	417	R 8 054 056	R 946 026	R 78 571	R 1 024 598	R 117
15000	625	R 10 553 799	R 1 239 645	R 117 857	R 1 357 502	R 155
20000	833	R 12 785 016	R 1 501 723	R 157 143	R 1 658 866	R 189
25000	1042	R 14 835 697	R 1 742 595	R 196 429	R 1 939 024	R 221
28000	1167	R 16 000 000	R 1 879 354	R 220 000	R 2 099 354	R 240
30000	1250	R 16 753 111	R 1 967 814	R 235 714	R 2 203 528	R 252
35000	1458	R 18 566 355	R 2 180 797	R 275 000	R 2 455 797	R 280
40000	1667	R 20 294 949	R 2 383 837	R 314 286	R 2 698 123	R 308
45000	1875	R 21 952 786	R 2 578 566	R 353 571	R 2 932 137	R 335
48000	2000	R 22 917 933	R 2 691 932	R 377 143	R 3 069 075	R 350

Appendix C Process and utility sinks and sources

Table C-1 Process sinks used in WaterPinch C-1
Table C-2 Process sources used in WaterPinch C-2
Table C-3 Utility sinks used in WaterPinch, including maximum flow and concentration limits C-3
Table C-4 Utility sources used in WaterPinch C-3

Table C-1 Process sinks used in optimisation model

Process sink (WaterPinch)	Flow (m^3/h)	Sink description
Woodyard in	14	Water to Woodyard
Kraft recovery in 1	76	Mill water to cooling towers and cooling water
Kraft recovery in 2	0.22	Turpentine condensate
Kraft recovery in 3	49	Mill water for mud-washing
Kraft pulping in 1	222	Wash water to Kraft Pulping
Kraft pulping in 2	42	Mill water to cooling tower make-up
Kraft pulping in 3	59	Mill water to seal water
NSSC pulping in 1	24	Wash water to NSSC Pulping
NSSC pulping in 2	108	Mill water to cooling water (becomes hot water)
NSSC pulping in 3	54	Mill water to seal water and spray ponds
NSSC pulping in 5	21	Water to Copeland reactor
Boilers in 1	**271**	Water to boilers section
	45.6	Domestic water to utilities
	79	Mill water to ash quenching
	16.6	Evaporator condensate to ash quenching
	52.2	Mill water to cooling tower
Boilers in 3	193.6	Domestic water to demineralisation plant (boiler feed)
PM4 in 3	79	Domestic water to Paper machine 4
PM4 in 4*	**393**	Diluted pulp to Paper machine 4
	184	Mill water to Paper Machines, including vacuum seal water, spray water and make-up water
	209	Pulp from Pulp Transfer to Paper Machine 4
Recovery2 in	86.4	Domestic water for seal water
Papermachine in 2	78	Dilution water from white water tower
Papermachine in 5	**1847**	Diluted pulp to Paper machines 1, 2 and 3
	1008	Mill water to Paper Machines 1, 2 and 3, including vacuum seal water, spray water and make-up water
	839	Pulp from Pulp Transfer to Paper Machines 1, 2 and 3
Pulp transfer in 2	**1064**	Pulp from pulping to Pulp Transfer
	649	Return White water from Paper Machines 1, 2 and 3
	240	Return White water from Paper Machine 4
	92	Hot water from NSSC
	83	Return from Clarifier 1
Pulp transfer in 5	9	Thickener spray water
Wasteplant in 1	83	Seal water
Wasteplant in 2	162	Wasteplant dilution water from pulp transfer (ex Paper Machine 2)
Wasteplant in 3	42	Clarifier 2 underflow return to Wasteplant

Table C-2 Process sources used in optimisation model

Process source (WaterPinch)	Flow (m^3/h)	Source description
Woodyard out	14	Woodyard effluent
Kraft Recovery out 1	263	Kraft condensate
Kraft Pulping out 1	66.1	Kraft ScrewPress effluent
Kraft Pulping out 2	0.22	Turpentine Condensate
NSSC Pulping out 1	92	NSSC hot water
NSSC Pulping out 2	48	NSSC Effluent
Boilers out 1	30	Demineralisation Plant Regeneration effluent
Boilers out 2	263	Boilers ash quench effluent
PM4 out 1	204	Paper machine 4 effluent
PM4 out 2	240	Paper Machines 1, 2 and 3 backwater to White Water Tower
Recovery2 out	88.2	Seal water and spills to drain
Paper Machines out 1	649	Paper Machine 4 backwater to White Water Tower
Paper Machines out 3	1119	Paper Machines Effluent
Paper Machines out 4	53	Cloudy filtrate tank overflow to waste drain
Pulp Transfer out 1	157.4	White water tower overflow to drain
Pulp Transfer out 2	162	Dilution water to Wasteplant
Pulp Transfer out 3	78	Dilution water to paper machines
Pulp Transfer out 4	839	Diluted pulp to Paper Machines 1, 2 and 3
Pulp Transfer out 5	209	Diluted pulp to Paper Machine 4
WastePlant out 1	40	Wasteplant effluent to drain
WastePlant out 2	74	Seal water to drain

Table C-3 Utility sinks used in the optimisation model, including maximum flow and concentration limits

Utility Sink	Maximum permissible flow (m^3/h)	Maximum Na (ppm)	Maximum DWS (ppm)	Maximum SS (ppm)	Maximum Ash (ppm)
Effluent in	0-2029	∞	∞	∞	∞
Clarifier 1 feed	1858	∞	∞	1200	0
Utility sink	100	∞	∞	∞	∞
Effluent Treatment (AS) Clean Side in	2500	∞	∞	220	6
RO 1 inlet	590	∞	∞	4	1
Vortex De-gritter inlet	300	∞	∞	100	2000
Ash Sink	-	∞	∞	∞	∞
Solid waste sink	-	∞	∞	∞	∞
DAF in	800	∞	∞	1400	200
Effluent Treatment 2 in	2000	∞	∞	200	40
Sand Filter inlet	2200	∞	∞	35	5
RO Brine Sink	-	∞	∞	∞	∞
Belt Press inlet	-	∞	∞	40000	40000
Brine Concentrator inlet	-	∞	∞	40	4
To Recovery Circuit	5	∞	∞	∞	∞

Table C-4 Utility sources used in the optimisation model

Utility Source	Maximum permissible flow (m^3/h)
Mill Water	1838.38
Domestic	481.9
Clarifier 1 overflow	-
Clarifier 1 underflow	-
Effluent Treatment (AS) Clean Side out	-
RO 1 permeate	-
RO 1 concentrate	-
Vortex De-gritter filtrate	-
Vortex De-gritter backwash	-
DAF treated water	-
DAF scum	-
Effluent Treatment 2 out	-
Sand Filter filtrate	-
Sand Filter backwash	-
Belt Press filtrate	-
Belt Press backwash	-
Brine Concentrator clean	-
Brine Concentrator dirty	-

Appendix D Bounds for optimisation model

Table D-1 Flow bounds set in WaterPinch D-2
Table D-2 Ztol bounds set in WaterPinch D-3

Table D-1 Flow bounds set in for the water pinch model

Process Sinks

Sources ↓ / Sinks →	Woodyard In [14]	Kraft Recovery In 1 [76]	Kraft Recovery In 2 [0.2]	Kraft Recovery In 3 [49]	Kraft Pulping In 1 [222]	Kraft Pulping In 2 [42]	Kraft Pulping In 3 [59]	NSSC Pulping In 1 [24]	NSSC Pulping In 2 [108]	NSSC Pulping In 3 [54]	NSSC Pulping In 5 [21]	Boilers In 1 [271]	Boilers In 3 [194]	PM4 In 3 [79]	PM4 In 4 [393]	Recovery2 In [86]	Paper Machines In 2 [78]	Paper Machines In 5 [1847]	Pulp Transfer In 2 [1064]	Pulp Transfer In 5 [9]	WastePlant In 1 [83]	WastePlant In 2 [162]	WastePlant In 3 [42]	Mix PMWatPulp In [1847]	MixPM4WatPulp In [393]	MixPulpTransfer In [1064]	MixBoilers In [271]	PrOp. 1 In [148]	PrOp. 2 In [123]
Process Sources																													
Woodyard out [14]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Kraft Recovery out 1 [263]								24																0	0	0		17	
Kraft Pulping out 1 [66]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Kraft Pulping out 2 [0.2]			0.2																										
NSSC Pulping out 1 [92]									0	0	0		0	0		0													0
NSSC Pulping out 2 [48]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Boilers out 1 [30]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Boilers out 2 [263]																													
PM4 out 1 [204]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
PM4 out 2 [240]																										240			
Recovery2 out [88]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Paper Machines out 1 [649]																										649			
Paper Machines out 3 [1119]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Paper Machines out 4 [53]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Pulp Transfer out 1 [157]	0	0		0	0	0	0		0		0		0	0		0				0	0			0	0	0			0
Pulp Transfer out 2 [162]																						162							
Pulp Transfer out 3 [78]																	78												
Pulp Transfer out 4 [1048]																								839	209				
WastePlant out 1 [40]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
WastePlant out 2 [74]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Mix PMWatPulp out [1847]																		1847											
MixPM4WatPulp out [393]															393														
MixPulpTransfer out [1064]																			1064										
MixBoilers out [271]												271																	
PrOp. 1 out [148]																											148		
PrOp. 2 out [123]																											123		
Utility Sources																													
Mill Water out 1 [1838]													0	0												0		52	
Domestic out 1 [482]	0									0																0			
Clar1 out 1 [+INF]				0	0								0	0		0								0	0				0
Clar1 out 2 [+INF]	0	0		0	0	0	0		0	0	0		0	0		0				0	0		42	0	0	0			0
Effluent Treatment (AS) Clean Side out [+INF]		0		0									0			0								0	0				0
RO 1 permeate [+INF]	0	0								0						0													
RO 1 concentrate [+INF]	0	0			0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Vortex Degritter filtrate [+INF]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0		79	0
Vortex Degritter backwash [+INF]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			
DAF out 1 [+INF]				0	0				0	0			0	0										0					
DAF out 2 [+INF]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
Effluent Treatment 2 out [+INF]				0									0											0	0				0
Clean Filter filtrate [+INF]				0						0			0			0													<45
Clean Filter backwash [+INF]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			0
BWF 1 filtrate [+INF]				0	0				0		0		0	0						0				0					
BWF 1 backwash [+INF]	0	0		0	0	0	0		0	0	0		0	0		0				0	0			0	0	0			
Concentrator clean [+INF]																													
Concentrator dirty [+INF]	0	0			0	0	0		0	0	0		0	0		0				0	0			0	0	0			0

Utility Sinks

Sources ↓ / Sinks →	Effluent In 1 [2029]	Clari In [1858]	UtSnk 1 [100]	Effluent Treatment (AS) Clean Side In [2500]	RO 1 Inlet [590]	Vortex Degritter Inlet [300]	Ash Sink [+INF]	Clar sink [+INF]	DAF In [800]	Effluent Treatment 2 In [2000]	Clean Filter Inlet [2200]	RO Brine Sink 2 [+INF]	BWF 1 Inlet [+INF]	Concentrator Inlet [+INF]	To Recovery Circuit [5]
Process Sources															
Woodyard out [14]	0	0		0	0	0	0	0		0	0	0	0	0	0
Kraft Recovery out 1 [263]															
Kraft Pulping out 1 [66]	0	0		0	0	0	0	0		0	0	0	0	0	0
Kraft Pulping out 2 [0.2]															
NSSC Pulping out 1 [92]		0		0	0	0	0	0		0		0	0	0	0
NSSC Pulping out 2 [48]	0	0		0	0	0	0	0		0	0	0	0	0	0
Boilers out 1 [30]							0	0		0		0	0	0	0
Boilers out 2 [263]						263									
PM4 out 1 [204]	0			0	0	0	0	0	0	0	0	0	0	0	0
PM4 out 2 [240]															
Recovery2 out [88]	0	0		0	0	0	0	0		0	0	0	0	0	0
Paper Machines out 1 [649]															
Paper Machines out 3 [1119]	0			0	0	0	0	0	0	0	0	0	0	0	0
Paper Machines out 4 [53]	0			0	0	0	0	0	0	0	0	0	0	0	0
Pulp Transfer out 1 [157]	0			0	0	0	0	0	0	0	0	0	0	0	0
Pulp Transfer out 2 [162]															
Pulp Transfer out 3 [78]															
Pulp Transfer out 4 [1048]															
WastePlant out 1 [40]	0	0		0	0	0	0	0		0	0	0	0	0	0
WastePlant out 2 [74]	0	0		0	0	0	0	0		0	0	0	0	0	0
Mix PMWatPulp out [1847]															
MixPM4WatPulp out [393]															
MixPulpTransfer out [1064]															
MixBoilers out [271]															
PrOp. 1 out [148]															
PrOp. 2 out [123]															
Utility Sources															
Mill Water out 1 [1838]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Domestic out 1 [482]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Clar1 out 1 [+INF]	0	0				0	0	0	0		0	0	0	0	0
Clar1 out 2 [+INF]	0	0		0	0	0	0	0	0	0	0	0		0	0
Effluent Treatment (AS) Clean Side out [+INF]		0		0		0	0	0	0	0		0	0	0	0
RO 1 permeate [+INF]	0	0		0	0	0	0	0	0	0	0	0	0	0	0
RO 1 concentrate [+INF]		0		0	0	0	0	0	0	0	0		<10		0
Vortex Degritter filtrate [+INF]	0	0		0	0	0	0	0		0	0	0	0	0	0
Vortex Degritter backwash [+INF]	0	0		0	0	0		0	0	0	0	0	0	0	0
DAF out 1 [+INF]		0				0	0	0	0			0	0	0	0
DAF out 2 [+INF]	0	0		0	0	0	0	0	0	0	0	0		0	0
Effluent Treatment 2 out [+INF]		0		0		0	0	0	0	0		0	0	0	0
Clean Filter filtrate [+INF]		0		0		0	0	0	0	0	0	0	0	0	0
Clean Filter backwash [+INF]	0	0		0	0	0	0	0	0	0	0	0		0	0
BWF 1 filtrate [+INF]					0	0	0	0			0	0	0	0	0
BWF 1 backwash [+INF]	0	0		0	0	0	0			0	0	0	0	0	0
Concentrator clean [+INF]	0			0	0					0				0	0
Concentrator dirty [+INF]	0	0		0	0	0	0	0	0	0	0		0	0	

Legend

0	Flow from source to sink is 0 – no match permitted
Flow	Compulsory match from sink to source
	Source to sink match not possible due to source being assigned to a specific sink (compulsory match)

Table D-2 Ztol bounds set for the water pinch model

Sink name	Ztol limit
Woodyard in [14]	7
Kraft Recovery in 1 [76]	10
Kraft Recovery in 2 [0.22]	-
Kraft Recovery in 3 [49]	5
Kraft Pulping in 1 [222]	10
Kraft Pulping in 2 [42]	10
Kraft Pulping in 3 [59]	5
NSSC Pulping in 1 [24]	-
NSSC Pulping in 2 [108]	10
NSSC Pulping in 3 [54]	5
NSSC Pulping in 5 [21]	5
Boilers in 1 [271]	-
Boilers in 3 [194]	-
PM4 in 3 [79]	5
PM4 in 4 [393]	-
Recovery2 in [86]	5
Paper Machines in 2 [78]	-
Paper Machines in 5 [1847]	-
Pulp Transfer in 2 [1064]	-
Pulp Transfer in 5 [9]	5
WastePlant in 1 [83]	5
WastePlant in 2 [162]	-
WastePlant in 3 [42]	-
Mix PMWatPulp in [1847]	-
MixPM4WatPulp in [393]	-
MixPulpTransfer in [1064]	-
MixBoilers in [271]	-
PrOp. 1 in [148]	-
PrOp. 2 in [123]	-

Appendix E *WinGEMS*™ and *WaterPinch*™ verification results

Table E-1 Base case verification results E-1
Table E-2 1895m^3/h effluent scenario verification results E-2
Table E-3 Concentration based limit, 1488m^3/h effluent scenario verification results E-3
Table E-4 Load based limit, 1100m^3/h effluent scenario verification results E-4
Table E-5 Load based limit, lowest cost scenario verification results E-5
Table E-6 Zero effluent scenario verification results E-6

Table E-1 Base case verification results

Source/sink		Flow (m^3/h)	Na (ppm)	DWS (ppm)	TSS (ppm)
Effluent in	WG	2115	200	262	123
	WP	2029	206	260	119
	Deviation	4.09	-3.15	0.53	3.09
Clar 1 in	WG	1568	213	309	1005
	WP	1563	223	307	986
	Deviation	0.31	-4.28	0.59	1.89
Clar 2 in	WG	644	167	426	1350
	WP	643	168	422	1311
	Deviation	0.11	-0.97	1.10	2.92
Degritter in	WG	261	39	217	2011
	WP	263	43	199	1907
	Deviation	-0.80	-8.44	8.04	5.15
Beltpress in	WG	55	186	354	22750
	WP	53	189	353	24042
	Deviation	3.74	-2.09	0.25	-5.68
Clar 1 out	WG	1504	213	247	94
	WP	1501	223	245	86
	Deviation	0.22	-4.28	0.59	8.83
Clar 2 out	WG	611	167	298	194
	WP	611	168	295	197
	Deviation	0.03	-0.97	1.10	-1.35
Boilers out	WG	261	39	217	2011
	WP	263	43	199	1907
	Deviation	-0.80	-8.44	8.04	5.15
Beltpress out	WG	52	185	354	400
	WP	50	189	353	420
	Deviation	3.97	-2.11	0.23	-5.00
PM Effluent	WG	1119	192	314	1118
	WP	1119	199	319	1101
	Deviation	-0.04	-3.61	-1.79	1.51
PM4 Effluent	WG	204	121	256	527
	WP	204	128	211	529
	Deviation	-0.02	-6.24	17.6	-0.41
WWT	WG	1064	191	351	735
	WP	1064	224	357	612
	Deviation	0.00	-17.7	-1.71	16.7
Screw Press Liquor	WG	66	664	1869	2410
	WP	66	664	1866	2400
	Deviation	-0.20	-0.01	0.11	0.41
Waste Plant Effluent 1	WG	40	241	429	3922
	WP	40	259	454	3900
	Deviation	-0.46	-7.42	-5.68	0.57
Waste Plant Effluent 2	WG	74	41	25	10
	WP	74	43	25	10
	Deviation	-0.36	-4.93	-0.08	0.00

Table E-2 1895m³/h effluent scenario verification results

Source/sink		Flow (m³/h)	Na (ppm)	DWS (ppm)	TSS (ppm)
Effluent in	WG	1893	218	127	40
	WP	1895	218	125	40
	Deviation	-0.12	-0.12	1.57	-0.85
Clar 1 in	WG	1537	200	341	1027
	WP	1533	201	336	1006
	Deviation	0.22	-0.32	1.52	2.07
DAF in	WG	500	189	496	720
	WP	501	191	494	710
	Deviation	-0.15	-0.84	0.26	1.37
Degritter in	WG	261	39	300	2012
	WP	263	43	271	1916
	Deviation	-0.80	-10.9	9.60	4.76
Beltpress in	WG	47	194	397	19920
	WP	44	195	396	24114
	Deviation	5.21	-0.56	0.17	-21.1
Effluent treatment1 in	WG	1307	196	304	104
	WP	1307	197	301	104
	Deviation	0.00	-0.50	0.97	-0.02
Clar 1 out	WG	1474	200	273	86
	WP	1472	201	269	86
	Deviation	0.13	-0.32	1.52	-0.41
DAF out	WG	474	189	347	106
	WP	476	191	346	107
	Deviation	-0.35	-0.81	0.29	-0.52
Degritter out	WG	248	39	299	211
	WP	250	43	271	206
	Deviation	-0.60	-10.6	9.25	2.58
Beltpress out	WG	44	194	397	420
	WP	42	195	396	420
	Deviation	3.68	-0.59	0.13	0.00
Effluent treatment1 out	WG	1305	196	76	24
	WP	1307	197	75	23
	Deviation	-0.16	-0.50	0.97	2.17
PM Effluent	WG	1119	205	336	1118
	WP	1119	205	340	1101
	Deviation	-0.04	-0.07	-1.32	1.52
PM4 Effluent	WG	204	133	275	527
	WP	204	134	235	529
	Deviation	-0.02	-0.87	14.5	-0.41
WWT	WG	1064	233	419	749
	WP	1064	242	401	618
	Deviation	0.00	-3.65	4.26	17.5
Screw Press Liquor	WG	66	664	1869	2410
	WP	66	664	1866	2400
	Deviation	-0.20	-0.01	0.11	0.41
Waste Plant Effluent 1	WG	40	259	377	3924
	WP	40	276	460	3900
	Deviation	-0.17	-6.63	-22.0	0.62
Waste Plant Effluent 2	WG	74	41	25	10
	WP	74	43	25	10
	Deviation	-0.36	-4.93	-0.08	0.00

Table E-3 Concentration based limit, 1488m³/h effluent scenario verification results

Source/sink		Flow (m^3/h)	Na (ppm)	DWS (ppm)	TSS (ppm)
Effluent in	WG	1487	261	128	38
	WP	1488	260	125	39
	Deviation	-0.07	0.41	2.26	-2.17
Clar 1 in	WG	1537	266	362	1027
	WP	1533	265	355	1003
	Deviation	0.22	0.48	1.85	2.31
DAF in	WG	500	238	513	720
	WP	501	238	510	710
	Deviation	-0.15	0.09	0.51	1.38
Degritter in	WG	261	39	300	2012
	WP	263	43	271	1916
	Deviation	-0.80	-10.9	9.60	4.76
Beltpress in	WG	60	290	317	15819
	WP	63	285	329	17243
	Deviation	-4.52	1.63	-3.89	-9.00
Effluent treatment1 in	WG	1239	257	312	92
	WP	1239	256	308	93
	Deviation	0.00	0.37	1.36	-0.43
Effluent treatment 2 in	WG	160	274	299	195
	WP	164	272	300	207
	Deviation	-2.64	0.76	-0.52	-6.56
Sandfilter in	WG	369	374	131	36
	WP	369	372	130	39
	Deviation	0.11	0.61	0.76	-8.20
Clar 1 out	WG	1474	266	289	86
	WP	1472	265	284	86
	Deviation	0.13	0.48	1.85	-0.39
DAF out	WG	480	238	359	106
	WP	476	238	357	107
	Deviation	0.74	0.12	0.54	-0.52
Degritter out	WG	248	39	299	211
	WP	250	43	271	206
	Deviation	-0.60	-10.6	9.25	2.58
Beltpress out	WG	55	290	317	400
	WP	60	285	329	420
	Deviation	-7.61	1.59	-3.93	-5.00
Effluent treatment1 out	WG	1237	257	78	20
	WP	1239	256	77	21
	Deviation	-0.15	0.37	1.37	-2.50
Effluent treatment 2 out	WG	160	274	75	40
	WP	164	272	75	46
	Deviation	-2.95	0.76	-0.52	-14.5
Sandfilter out	WG	351	374	131	4
	WP	350	372	130	4
	Deviation	0.11	0.61	0.76	-5.45
PM Effluent	WG	1119	282	360	1118
	WP	1119	279	360	1099
	Deviation	-0.04	1.10	-0.24	1.67
PM4 Effluent	WG	204	150	280	527
	WP	204	151	246	529
	Deviation	-0.02	-1.16	12.3	-0.41
WWT	WG	1064	296	437	749
	WP	1064	300	420	617
	Deviation	0.00	-1.48	3.90	17.7
Screw Press Liquor	WG	66	664	1869	2410
	WP	66	664	1866	2400
	Deviation	-0.20	-0.01	0.11	0.41
Waste Plant Effluent 1	WG	40	325	394	3924
	WP	40	332	463	3900
	Deviation	-0.17	-2.35	-17.5	0.62
Waste Plant Effluent 2	WG	74	335	132	11
	WP	74	330	130	10
	Deviation	-0.36	1.68	0.93	6.98

Table E-4 Load based limit, 1100m³/h effluent scenario verification results

Source/sink		Flow (m³/h)	Na (ppm)	DWS (ppm)	TSS (ppm)
Effluent in	WG	1101	335	219	83
	WP	1100	336	215	84
	Deviation	0.09	-0.17	1.72	-1.49
Clar 1 in	WG	1537	308	394	1027
	WP	1533	309	387	1000
	Deviation	0.22	-0.43	1.95	2.67
DAF in	WG	500	229	516	720
	WP	501	229	512	710
	Deviation	-0.15	-0.19	0.83	1.39
Degritter in	WG	261	39	300	2012
	WP	263	43	271	1916
	Deviation	-0.80	-10.9	9.60	4.76
Beltpress in	WG	82	269	287	11799
	WP	83	268	292	13197
	Deviation	-1.51	0.45	-1.78	-11.8
Effluent treatment1 in	WG	1016	284	329	92
	WP	1016	285	324	92
	Deviation	0.00	-0.36	1.59	-0.40
Sandfilter in	WG	776	272	143	39
	WP	776	273	142	39
	Deviation	0.02	-0.33	1.17	-0.88
Clar 1 out	WG	1474	308	316	86
	WP	1472	309	309	86
	Deviation	0.13	-0.43	1.95	-0.34
DAF out	WG	478	229	362	106
	WP	476	229	358	107
	Deviation	0.43	-0.16	0.86	-0.52
Degritter out	WG	248	39	299	211
	WP	250	43	271	206
	Deviation	-0.60	-10.6	9.25	2.58
Beltpress out	WG	78	269	287	420
	WP	79	268	292	420
	Deviation	-1.04	0.43	-1.80	0.00
Effluent treatment1 out	WG	1015	284	82	20
	WP	1016	285	81	20
	Deviation	-0.14	-0.36	1.58	-1.45
Sandfilter out	WG	737	272	143	4
	WP	737	273	142	4
	Deviation	0.01	-0.33	1.17	2.11
PM Effluent	WG	1119	329	398	1119
	WP	1119	329	395	1097
	Deviation	-0.04	0.06	0.77	1.91
PM4 Effluent	WG	204	160	288	527
	WP	204	164	263	529
	Deviation	-0.02	-2.44	8.51	-0.41
WWT	WG	1064	332	466	749
	WP	1064	340	453	614
	Deviation	0.00	-2.38	2.72	18.0
Screw Press Liquor	WG	66	664	1869	2410
	WP	66	664	1866	2400
	Deviation	-0.20	-0.01	0.11	0.41
Waste Plant Effluent 1	WG	40	364	418	3924
	WP	40	371	467	3900
	Deviation	-0.17	-2.13	-11.7	0.62
Waste Plant Effluent 2	WG	74	253	144	11
	WP	74	251	142	10
	Deviation	-0.36	0.50	1.30	9.08

Table E-5 Load based limit, lowest cost scenario verification results

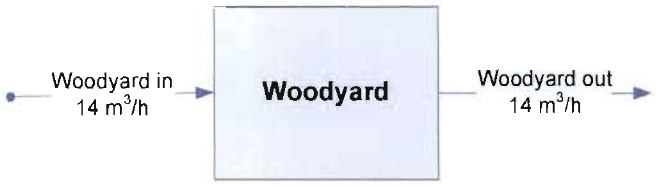
Source/sink		Flow (m^3/h)	Na (ppm)	DWS (ppm)	TSS (ppm)
Effluent in	WG	711	462	336	133
	WP	714	465	332	138
	Deviation	-0.32	-0.50	1.30	-3.47
Clar 1 in	WG	1535	559	426	1028
	WP	1533	564	418	997
	Deviation	0.08	-0.88	1.78	3.04
DAF in	WG	501	286	514	723
	WP	501	283	507	710
	Deviation	-0.08	0.90	1.35	1.76
Degritter in	WG	261	39	300	2012
	WP	263	43	271	1916
	Deviation	-0.80	-10.9	9.60	4.76
Beltpress in	WG	95	481	258	9546
	WP	102	477	268	10891
	Deviation	-7.61	0.92	-4.04	-14.1
Effluent treatment1 in	WG	903	559	340	83
	WP	903	564	334	86
	Deviation	0.00	-0.88	1.78	-3.15
Sandfilter in	WG	1150	530	144	38
	WP	1148	532	142	37
	Deviation	0.12	-0.50	1.63	1.26
Clar 1 out	WG	1476	559	340	83
	WP	1472	564	334	86
	Deviation	0.29	-0.88	1.78	-3.15
DAF out	WG	480	286	360	106
	WP	476	283	355	107
	Deviation	0.78	0.93	1.38	-0.52
Degritter out	WG	248	39	299	211
	WP	250	43	271	206
	Deviation	-0.60	-10.6	9.25	2.58
Beltpress out	WG	90	481	258	420
	WP	97	477	268	420
	Deviation	-7.71	0.90	-4.06	0.00
Effluent treatment1 out	WG	901	559	85	19
	WP	903	564	84	17
	Deviation	-0.13	-0.88	1.77	9.47
Sandfilter out	WG	1092	530	144	4
	WP	1091	532	142	4
	Deviation	0.12	-0.50	1.63	-0.70
PM Effluent	WG	1118	612	432	1119
	WP	1119	613	426	1095
	Deviation	-0.06	-0.18	1.36	2.15
PM4 Effluent	WG	204	258	304	527
	WP	204	271	289	529
	Deviation	-0.02	-4.83	4.75	-0.40
WWT	WG	1064	555	491	749
	WP	1064	577	486	613
	Deviation	0.00	-3.96	0.92	18.2
Screw Press Liquor	WG	66	664	1869	2410
	WP	66	664	1866	2400
	Deviation	-0.20	-0.01	0.11	0.41
Waste Plant Effluent 1	WG	40	614	443	3929
	WP	40	602	472	3900
	Deviation	0.60	1.91	-6.55	0.74
Waste Plant Effluent 2	WG	74	502	116	13
	WP	74	492	107	10
	Deviation	-0.36	2.10	8.06	25.2

Table E-6 Zero effluent scenario verification results

Source/sink		Flow (m^3/h)	Na (ppm)	DWS (ppm)	TSS (ppm)
Effluent in	WG	0	0	0	0
	WP	0	0	0	0
	Deviation	0.00	0.00	0.00	0.00
Clar 1 in	WG	1537	665	440	1028
	WP	1533	662	436	997
	Deviation	0.22	0.44	0.87	3.02
DAF in	WG	679	456	443	626
	WP	682	452	436	625
	Deviation	-0.46	0.97	1.74	0.18
RO in	WG	559	595	146	4
	WP	559	592	144	4
	Deviation	-0.01	0.50	1.39	1.56
Degritter in	WG	292	280	260	1796
	WP	293	268	226	1723
	Deviation	-0.24	4.27	13.0	4.06
Beltpress in	WG	158	726	267	6880
	WP	160	712	267	8411
	Deviation	-1.41	1.87	0.00	-22.3
Effluent treatment1 in	WG	1426	645	348	87
	WP	1424	642	345	87
	Deviation	0.15	0.43	0.94	-0.07
Sandfilter in	WG	1939	595	146	39
	WP	1939	592	144	38
	Deviation	0.00	0.50	1.39	1.48
Concentrator in	WG	60	2857	725	20
	WP	60	2863	716	20
	Deviation	0.00	-0.23	1.29	1.56
Clar 1 out	WG	1474	665	352	86
	WP	1472	662	349	86
	Deviation	0.12	0.44	0.87	-0.28
DAF out	WG	649	456	310	96
	WP	648	452	305	94
	Deviation	0.11	1.00	1.76	1.91
RO permeate	WG	447	29	2	0
	WP	447	24	1	0
	Deviation	-0.01	18.4	12.5	0.00
Degritter out	WG	277	280	260	189
	WP	278	268	226	208
	Deviation	-0.40	4.27	13.0	-9.92
Beltpress out	WG	150	725	266	420
	WP	152	712	267	420
	Deviation	-1.84	1.85	-0.02	0.00
Effluent treatment1 out	WG	1424	645	87	18
	WP	1424	642	86	18
	Deviation	0.01	0.43	0.94	0.70
Sandfilter out	WG	1842	595	146	4
	WP	1842	592	144	4
	Deviation	0.00	0.50	1.39	1.56
Concentrator clean	WG	48	36	9	0
	WP	48	29	7	0
	Deviation	0.00	19.8	21.0	0.00
PM Effluent	WG	1119	695	440	1119
	WP	1119	692	439	1095
	Deviation	-0.04	0.51	0.40	2.14
PM4 Effluent	WG	204	464	346	527
	WP	204	464	335	529
	Deviation	-0.03	0.11	3.18	-0.37
WWT	WG	1064	687	511	749
	WP	1064	694	511	613
	Deviation	0.00	-1.09	0.14	18.2
Screw Press Liquor	WG	66	664	1869	2410
	WP	66	654	1861	2400
	Deviation	-0.20	1.48	0.40	0.41
Waste Plant Effluent 1	WG	40	710	453	3924
	WP	40	717	475	3900
	Deviation	-0.16	-0.91	-4.99	0.62
Waste Plant Effluent 2	WG	74	547	148	11
	WP	74	536	146	10
	Deviation	-0.36	2.02	1.04	9.08

Appendix F Mass transfer equations derived for process units

Figure F-1 Mass transfer equations derived for the Woodyard F-2
Figure F-2 Mass transfer equations derived for the NSSC pulping section F-2
Figure F-3 Mass transfer equations derived for the Kraft pulping section F-3
Figure F-4 Mass transfer equations derived for the Kraft Recovery section F-3
Figure F-5 Mass transfer equations derived for the Recovery 2 section F-3
Figure F-6 Mass transfer equations derived for the Boilers section F-4
Figure F-7 Mass transfer equations derived for the Pulp Transfer section F-4
Figure F-8 Mass transfer equations derived for Paper Machines 1, 2 and 3 .... F-5
Figure F-9 Mass transfer equations derived for Paper Machine 4 .... F-5
Figure F-10 Mass transfer equations derived for the Waste Plant F-6



Woodyard out	
Na	$C_{out} = 0.65 * C_{in} + 0$
DWS	$C_{out} = \frac{(C_{in} * F_{in} + 1026.6)}{F_{out}}$
SS	$C_{out} = \frac{(C_{in} * F_{in} + 3808)}{F_{out}}$
Ash	$C_{out} = 0$

Figure F-1 Mass transfer equations derived for the Woodyard

NSSCPulping out 1	
Na	$C_{out} = C_{in}$
DWS	$C_{out} = C_{in}$
SS	$C_{out} = C_{in}$
Ash	$C_{out} = 0$

NSSC Pulping out 2	
Na	$C_{out} = 0.7 * C_{in} + 43$
DWS	$C_{out} = 0.72 * C_{in} + 478$
SS	$C_{out} = 0.2 * C_{in} + 18$
Ash	$C_{out} = 0$

Figure F-2 Mass transfer equations derived for the NSSC pulping section

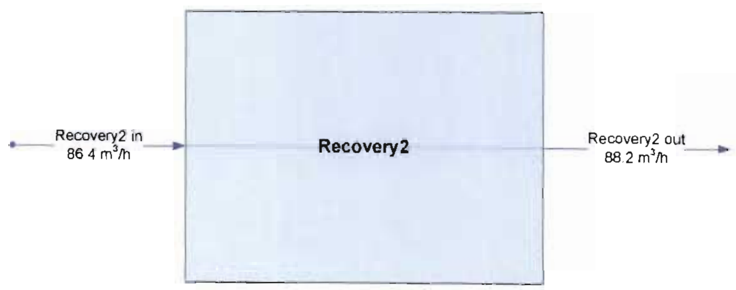
Kraft Pulping out 1	
Na	$C_{out} = 1.92 * C_{in} + 539$
DWS	$C_{out} = 0.91 * C_{in} + 1346$
SS	$C_{out} = \frac{(C_{in} * F_{in} + 158592)}{F_{out}}$
Ash	$C_{out} = 0$

Kraft Pulping out 2	
Na	$C_{out} = 600$
DWS	$C_{out} = 60$
SS	$C_{out} = 0$
Ash	$C_{out} = 0$

Figure F-3 Mass transfer equations derived for the Kraft pulping section

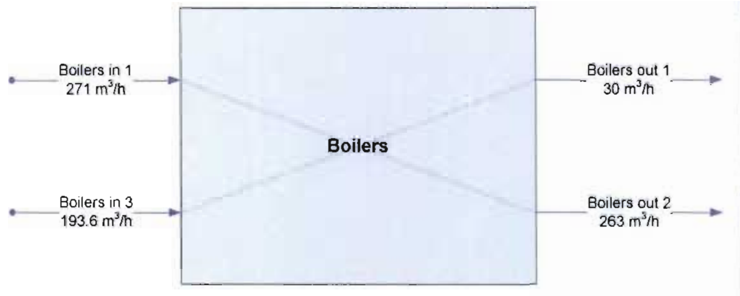
Kraft Recovery out 1	
Na	$C_{out} = 0.297 * C_{in} + 52.8$
DWS	$C_{out} = 0.25 * C_{in} + 565.7$
SS	$C_{out} = 0$
Ash	$C_{out} = 0$

Figure F-4 Mass transfer equations derived for the Kraft Recovery section



Recovery2 out	
Na	$C_{out} = C_{in} + 258$
DWS	$C_{out} = C_{in} + 345$
SS	$C_{out} = 5$
Ash	$C_{out} = 0$

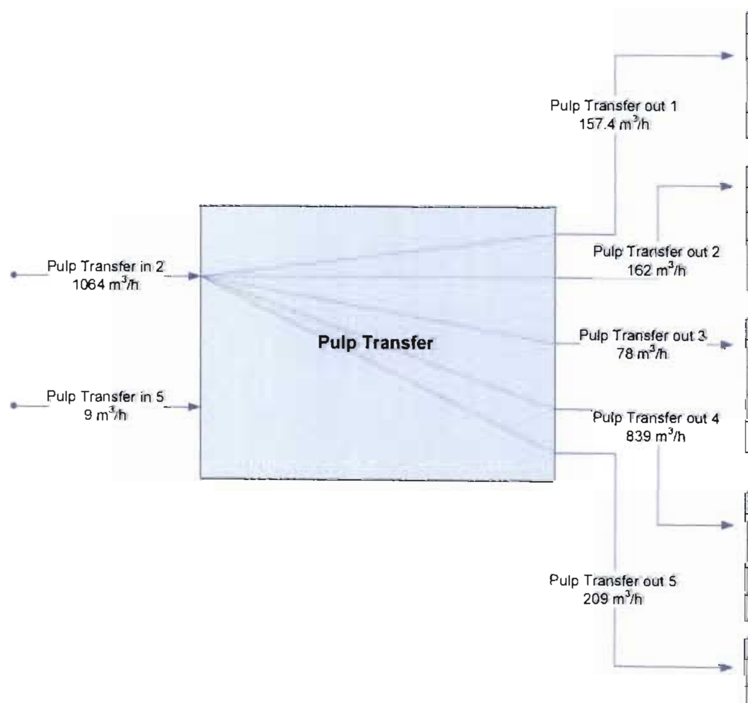
Figure F-5 Mass transfer equations derived for the Recovery 2 section



Boilers out 1	
Na	$C_{out} = C_{in} + 1684$
DWS	$C_{out} = C_{in}$
SS	$C_{out} = C_{in} + 25$
Ash	$C_{out} = 0$

Boilers out 2	
Na	$C_{out} = C_{in}$
DWS	$C_{out} = C_{in} + 140$
SS	$C_{out} = C_{in}$
Ash	$C_{out} = 0.18 * C_{in} + 1900$

Figure F-6 Mass transfer equations derived for the Boilers section



Pulp Transfer out 1	
Na	$C_{out} = 0.992 * C_{in} + 1.64$
DWS	$C_{out} = 0.98 * C_{in} + 5.03$
SS	$C_{out} = 1 * C_{in} + 25$
Ash	$C_{out} = 0$

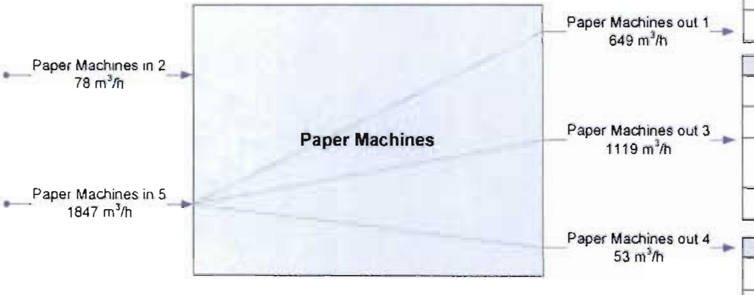
Pulp Transfer out 2	
Na	$C_{out} = 0.968 * C_{in} + 62.3$
DWS	$C_{out} = 0.88 * C_{in} + 162$
SS	$C_{out} = C_{in}$
Ash	$C_{out} = 0$

Pulp Transfer out 3	
Na	$C_{out} = 0.992 * C_{in} + 1.64$
DWS	$C_{out} = 0.98 * C_{in} + 5.03$
SS	$C_{out} = C_{in} - 7$
Ash	$C_{out} = 0$

Pulp Transfer out 4	
Na	$C_{out} = 0.823 * C_{in} + 171.83$
DWS	$C_{out} = 1.42 * C_{in} + 176.4$
SS	$C_{out} = 40000$
Ash	$C_{out} = 0$

Pulp Transfer out 5	
Na	$C_{out} = 0.766 * C_{in} + 107.25$
DWS	$C_{out} = 1.41 * C_{in} + 54.9$
SS	$C_{out} = 40000$
Ash	$C_{out} = 0$

Figure F-7 Mass transfer equations derived for the Pulp Transfer section

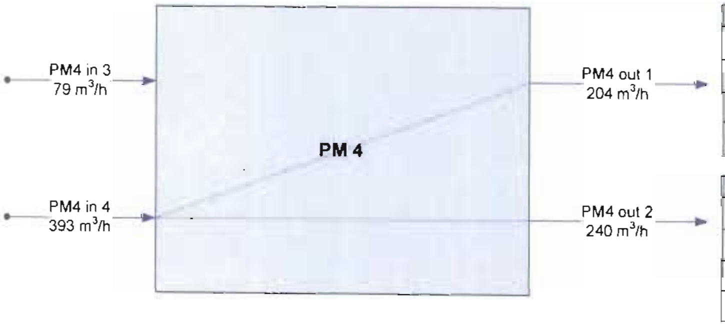


Paper Machines out 1	
Na	$C_{out} = 0.98 * C_{in} + 91.7$
DWS	$C_{out} = 0.8 * C_{in} + 177.6$
SS	$C_{out} = \frac{(C_{in} * F_{in} - 3.3*10^7)}{F_{out}}$
Ash	$C_{out} = 0$

Paper Machines out 3	
Na	$C_{out} = 1.04 * C_{in} + 7.6$
DWS	$C_{out} = 0.72 * C_{in} + 84.4$
SS	$C_{out} = \frac{(C_{in} * F_{in} - 3.2*10^7)}{F_{out}}$
Ash	$C_{out} = 0$

Paper Machines out 4	
Na	$C_{out} = 0.98 * C_{in} + 57.5$
DWS	$C_{out} = 0.82 * C_{in} + 159.9$
SS	$C_{out} = \frac{(C_{in} * F_{in} - 3.35*10^7)}{F_{out}}$
Ash	$C_{out} = 0$

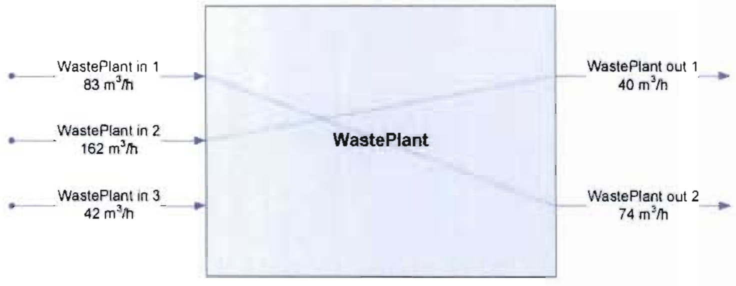
Figure F-8 Mass transfer equations derived for Paper Machines 1, 2 and 3



PM4 out 1	
Na	$C_{out} = 0.75 * C_{in} + 3.2$
DWS	$C_{out} = 0.72 * C_{in} - 11.1$
SS	$C_{out} = 529$
Ash	$C_{out} = 0$

PM4 out 2	
Na	$C_{out} = 0.95 * C_{in} + 4.1$
DWS	$C_{out} = 0.96 * C_{in} + 5.64$
SS	$C_{out} = 646$
Ash	$C_{out} = 0$

Figure F-9 Mass transfer equations derived for Paper Machine 4



WastePlant out 1	
Na	$C_{out} = 1.01 * C_{in} - 22.9$
DWS	$C_{out} = 0.16 * C_{in} + 377.7$
SS	$C_{out} = 3900$
Ash	$C_{out} = 0$

WastePlant out 2	
Na	$C_{out} = 0.89 * C_{in} + 6.63$
DWS	$C_{out} = 0.905 * C_{in} + 2.405$
SS	$C_{out} = 10$
Ash	$C_{out} = 0$

Figure F-10 Mass transfer equations derived for the Waste Plant

Appendix G Layout drawings for main scenarios

Figure G-1 Base case layout drawing G-2
Figure G-2 Lowest cost option, 1895m^3/h layout drawing G-3
Figure G-3 Concentration based limit, 1488m^3/h layout drawing G-4
Figure G-4 Load based limit, 1100m^3/h layout drawing G-5
Figure G-5 Load based limit, with discharge tariffs, 714m^3/h layout drawing G-6
Figure G-6 Zero effluent discharge layout drawing G-7

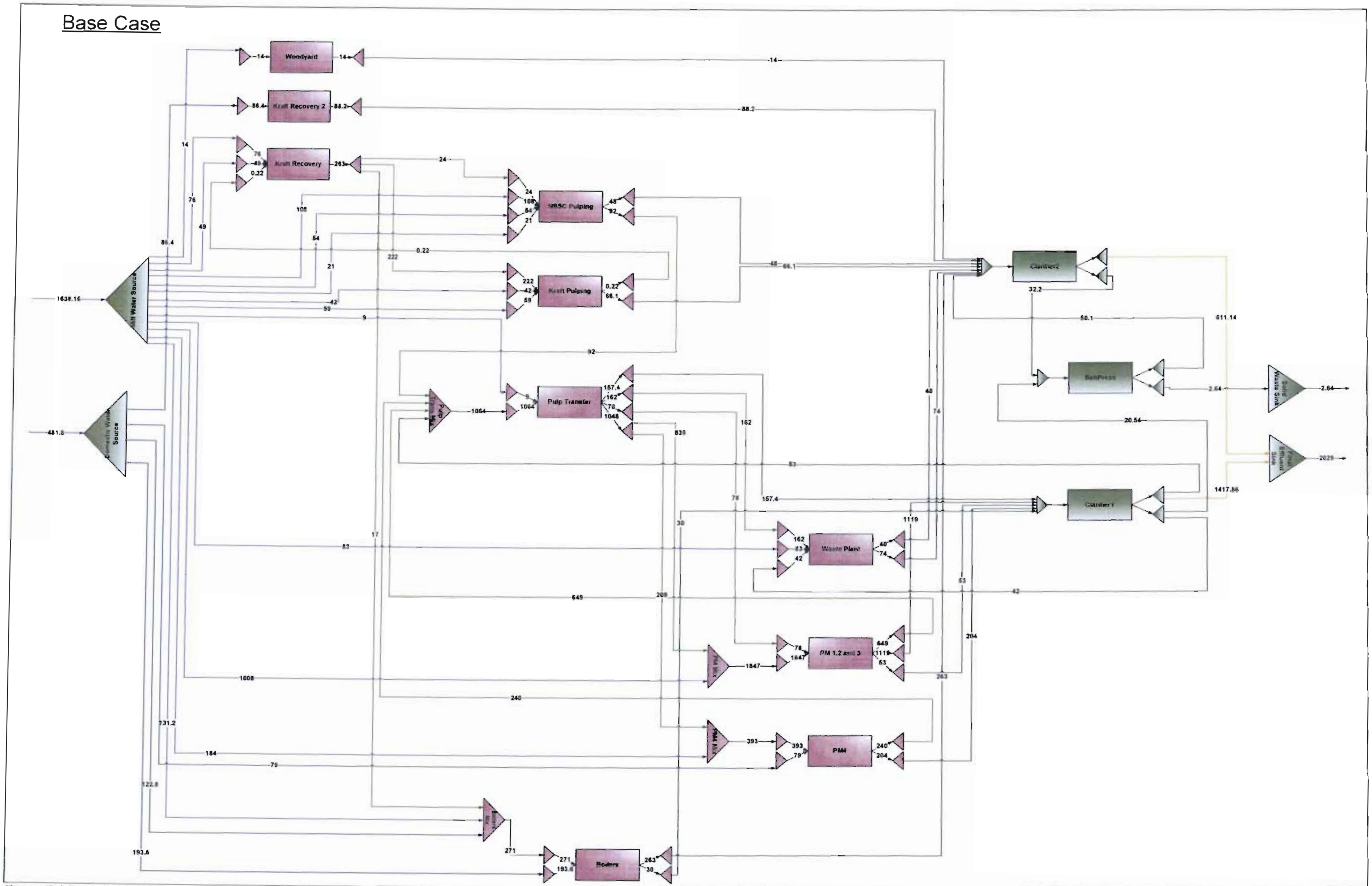


Figure G-1 Base case layout drawing

No discharge tariffs, lowest cost option, 1895m^3/h effluent

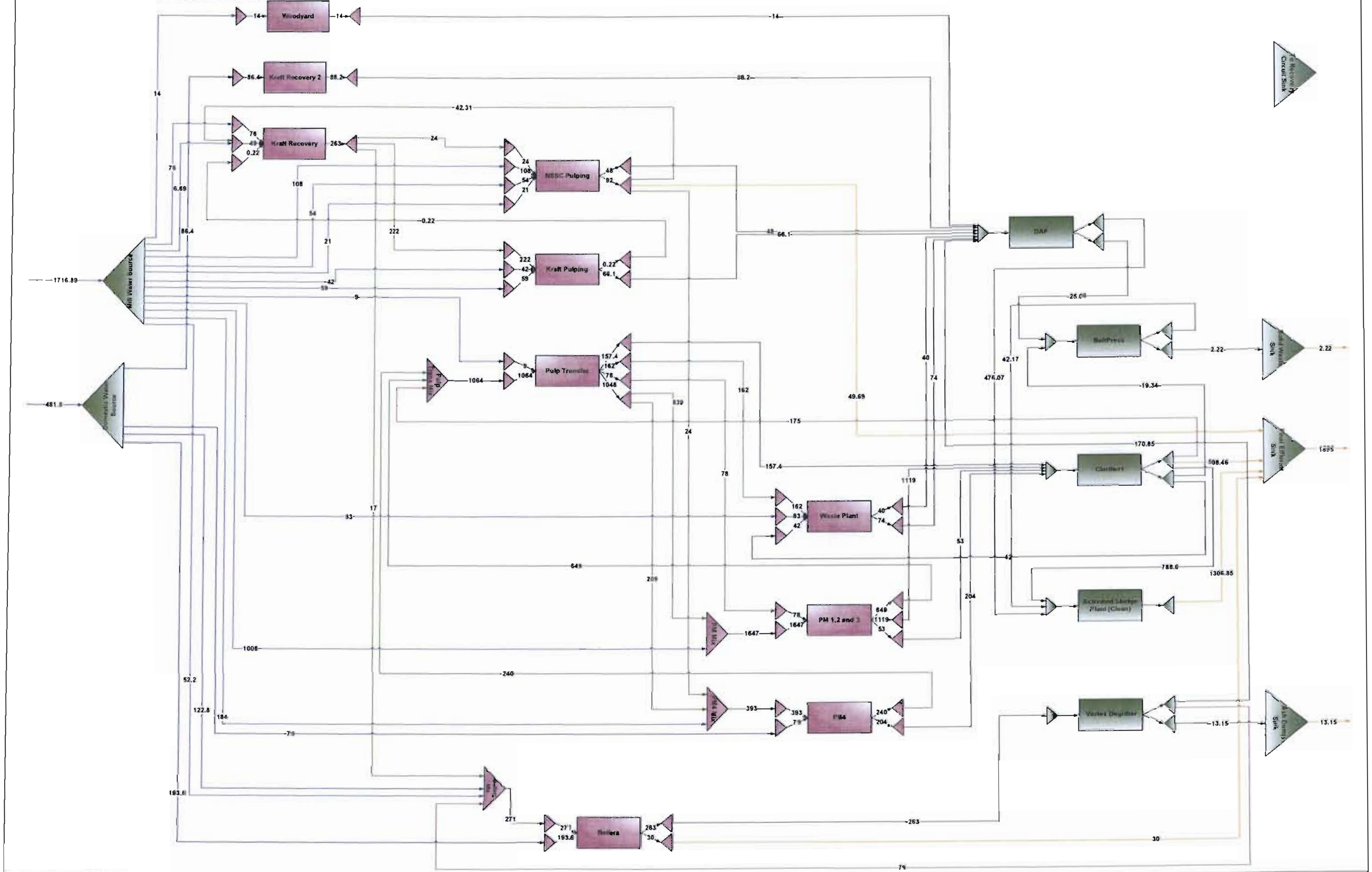


Figure G-2 Lowest cost option, 1895m^3/h layout drawing

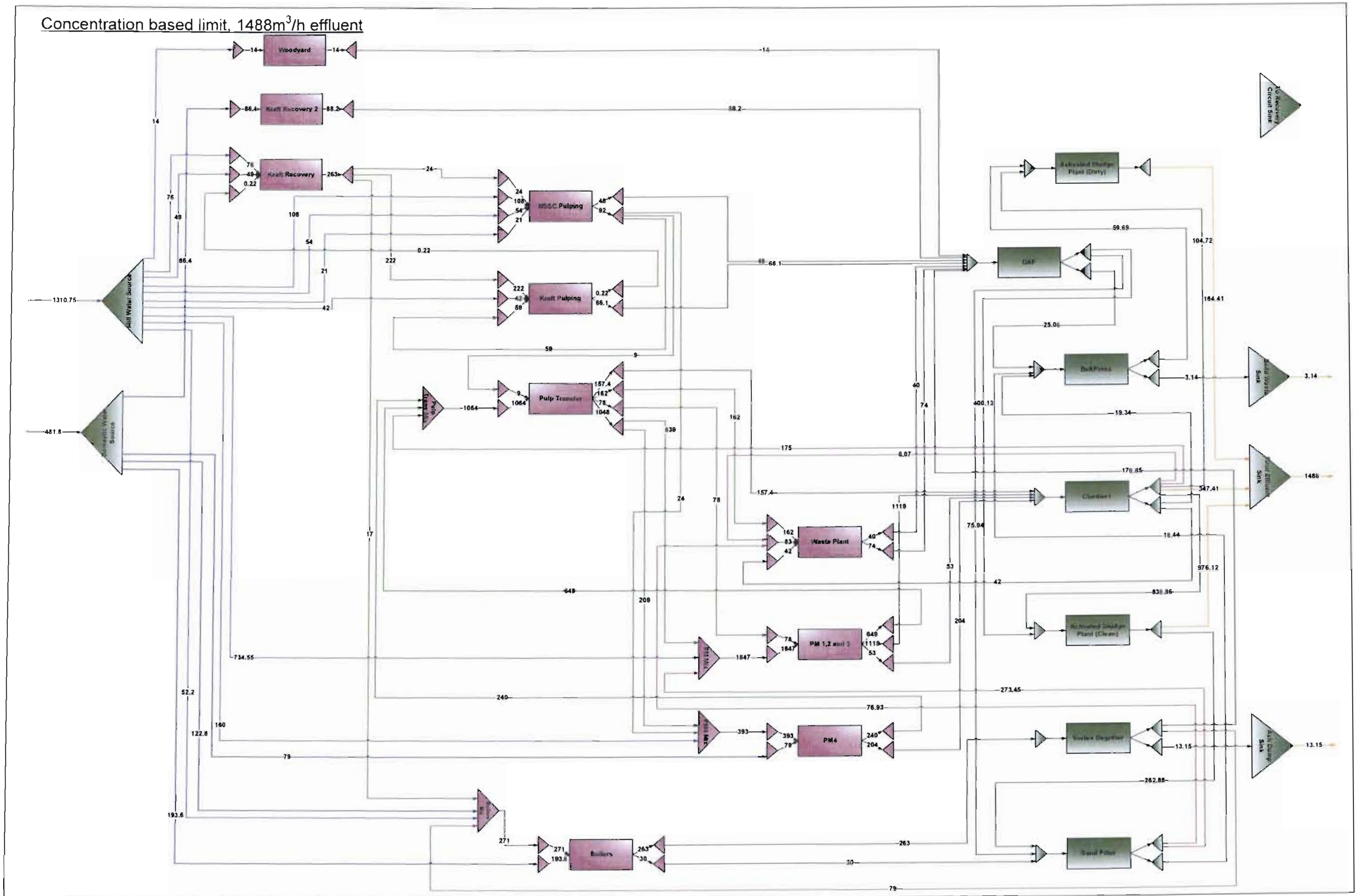


Figure G-3 Concentration based limit, 1488m³/h layout drawing

Load based limit, 1100m³/h effluent

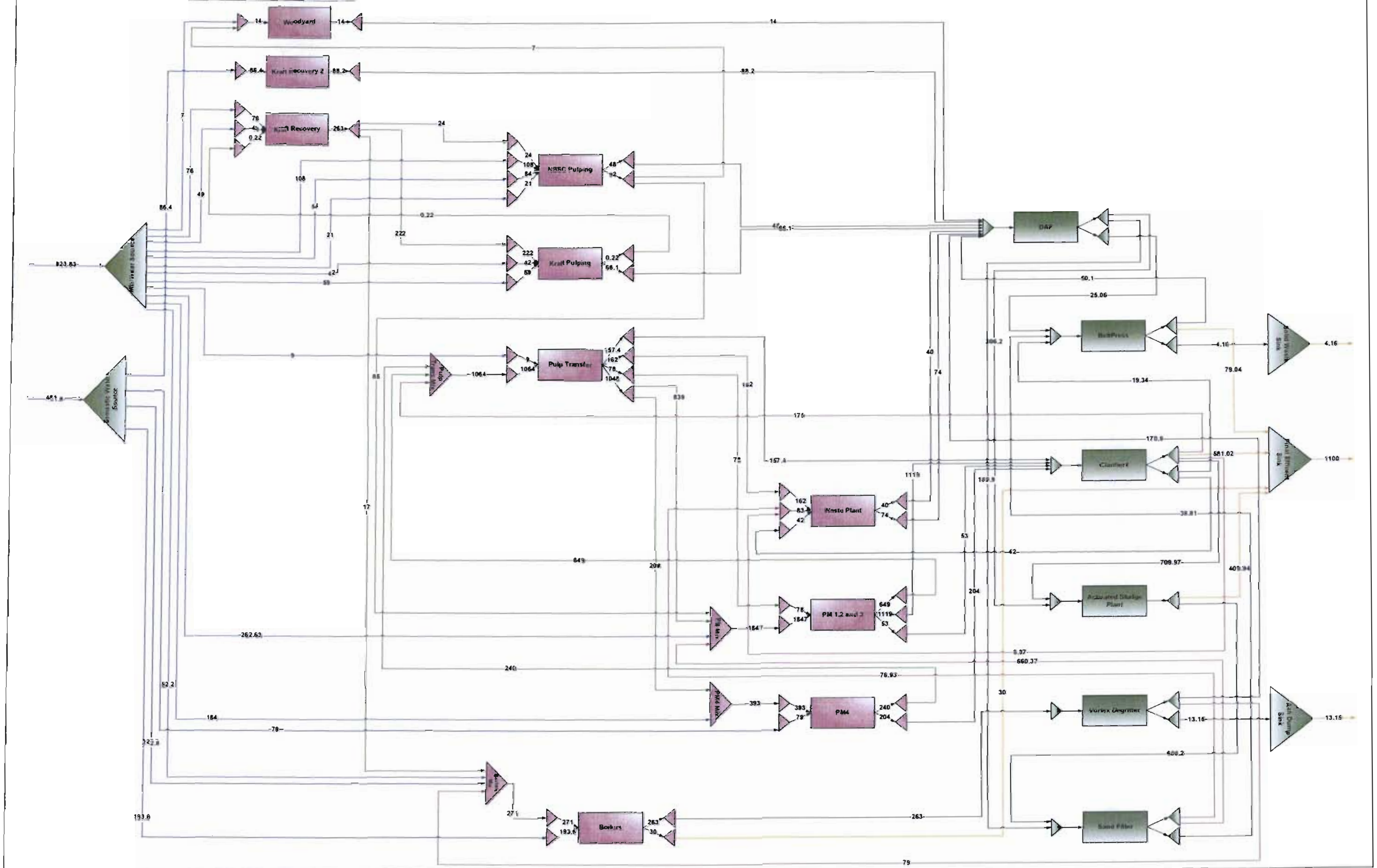


Figure G-4 Load based limit, 1100m³/h layout drawing

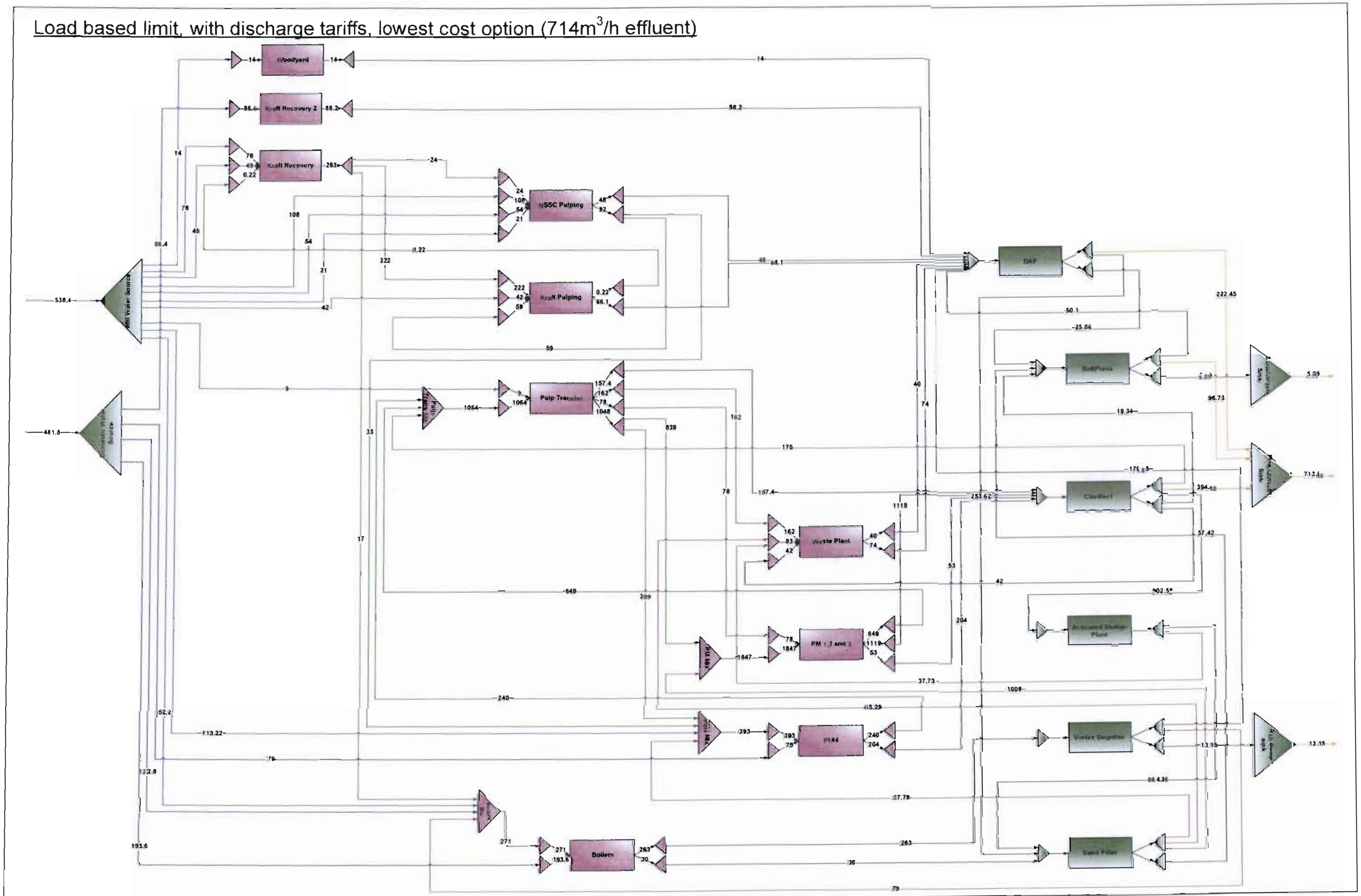


Figure G-5 Load based limit, with discharge tariffs, 714m^3/h layout drawing

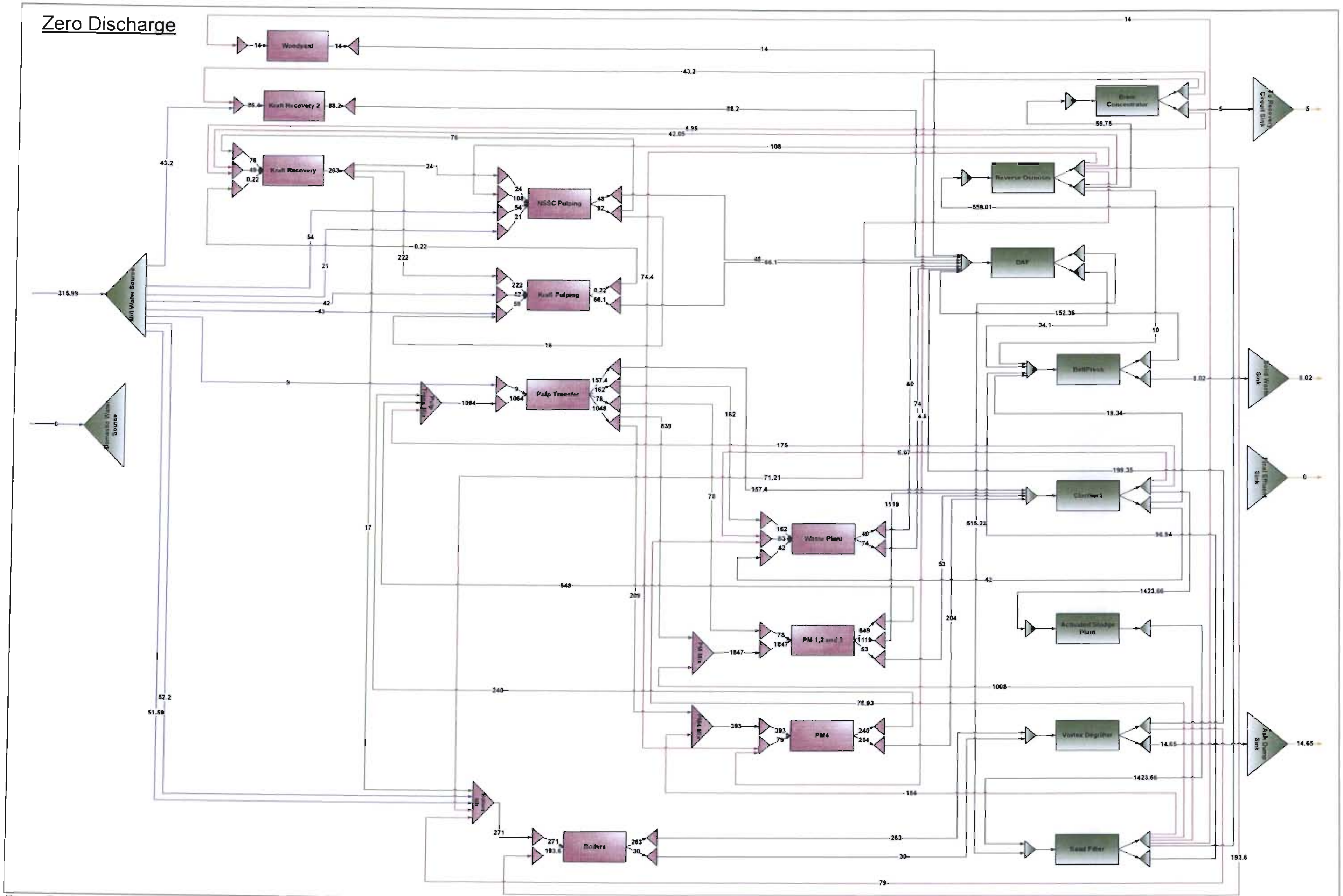


Figure G-6 Zero effluent discharge layout drawing