WASTE WATER MINIMIZATION USING WATER PINCH TECHNOLOGY

A DISSERTATION

Submitted in partial fulfilment of the requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
CHEMICAL ENGINEERING
(With Specialization in Industrial Pollution Abatement)

By

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CANDIDATE'S DECLARATION

I hereby declare that the report which is being presented in this dissertation work **"WASTE WATER MINIMIZATION USING WATER PINCH TECHNOLOGY"** in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in Chemical Engineering, specialization in **Industrial Pollution Abatement** submitted in Chemical Engineering Deptt. , Indian Institute of Technology, Roorkee is an authentic record of my own work carried out during a period from July 2007 to June 2008 under the supervision of **Dr. Bikash Mohanty**, Professor, Chemical Engineering Dept. Indian Institute of Technology, Roorkee.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

M.D.Dakwala

DATE: JUNE 22, 2008 **(DAKWALA MIHIR DUSHYANT)**

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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If one is more concerned in human beings than in econometrics, this acknowledgment is doubtlessly more exciting to read than the remaining chapters of this thesis as it enlighten (a little bit) more about the interpersonal interaction of me and the way in which I experiences the world.

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Always remember ***"We are soldiers, We fight where we are told, and we will win where we fight."***

DAKWALA MIHIR DUSHYANT

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ABSTRACT

Water is a vital component for many industrial operations, and is utilized for a wide range of purposes in industrial processes. The rapid growth in population, coupled with industrialization and urbanization, resulted in an increased demand for water, leading to serious consequences on the environment. The cost and scarcity of water beside stricter regulations on industrial effluents have become a significant factor in commodity material manufacturing. As water supply and treatment costs increase, there will be increasing pressure on the chemical process industries to reduce water consumption.

There are many types of technologies/methodologies available to save fresh water and reduce waste water generation. Water Pinch is one of the most important technologies for wastewater minimization, treats the water utilization processes of an industry as an organic whole, and considers how to allocate the water quantity and quality to each water using unit, so that water reuse is maximized within the system and simultaneously the wastewater generation is minimized.

In this dissertation, sincere efforts had been put to demonstrate, the potential of water pinch technology at real world of industries. Different case studies are discussed in detail. All cases had been considered as retrofitting problems and had been solved very meticulously considering existing piping and plant layouts, present cost of power and recent market price of different sizes of pipes.

Two industries mainly targeted due to accessibility of data: (1) Starch Industry from Gujarat and (2) Glass Industry from Uttarakhand. Four different cases of starch industry had been solved which are based on conventional water pinch problems. The case of glass industry is based on special case of water conservation through energy management.

The first problem is viewed as a single contaminant problem and all the three modes of water integration i.e. *reuse, regeneration-reuse, regeneration –recycling* are demonstrated. The DM water consumption is 50 tph before modification and after modification using water pinch it reduces to 31.9 tph *(reuse)*, 21.6 tph (*regeneration-reuse*) and 12 tph (*regeneration-recycling*). The results obtained from the present analysis are compared well with the results obtained from well established software ASPEN WATER which uses mathematical programming approach based on MINLP. The cost benefit analysis illustrates that the profit obtained in the case of reuse is 22,01,914 INR per year and the pay back period for the *regeneration-reuse* and *regeneration –recycling* are 2.5 and 2.3 month.

The second problem is also viewed as a single contaminant problem and all the three modes of water integration i.e. *reuse, regeneration-reuse, regeneration –recycling* are applied. The DM water consumption is 69 tph before modification and after modification using water pinch it reduces to 59.8 tph *(reuse)*, 34.5 tph (*regeneration-reuse*) and 30 tph (*regeneration-recycling*). The cost benefit analysis illustrates that the profit obtained in the case of reuse is 17,63,914 INR per year and the pay back period for the *regeneration-reuse* and *regeneration –recycling* are 1.8 and 1.1 month.

The third problem is tackled as a single contaminant problem which involves ten operations and only approach of water *reuse* is applied. The DM water consumption is 337 tph before modification and after modification using water pinch it reduces to 221.5 tph *(reuse)*. The cost benefit analysis illustrates that the profit obtained in the case of reuse is 5,43,120 INR per year.

The fourth problem is identified as a multi contaminant, *reuse* problem. The fresh water consumption and DM water consumption are 100 tph and 51 tph respectively before modification and the network is dealing with three major contaminant such as total organic content (TOC), total dissolved solids (TDS) and total suspended solids (TSS). The improved water using network designed for the present work consumed less DM & fresh water. The reductions are of the tune of 28% and 64.38 % for DM and fresh water respectively. Due to alteration in piping, there will be a saving of 4,06,026 INR per year, which will be utilized for development of efficient environment policy for the company.

The concept of water-pinch coupled with thermal analysis is applied on cooling water networks of different sections, namely, furnace melting, neck- refining & spout and tin bath, of a Glass industry of India commissioned in the year 2006. The analysis takes in to account mixing of multiple intermediate cooling water streams to satisfy the constraints of the network. Different proposal had been worked out and different strategies had been proposed for summer and winter season. The results are very encouraging and there will be huge benefit in terms of power and fresh water consumption, if the proposed modified networks have been put into real operations. Two different operational strategies have been proposed to achieve maximum *reuse* of water. The maximum projected savings will be of 11,55,978 INR for summer season and 14,16,846 INR for winter season operations.

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NOMENCLATURES

$C_{i,in}^{\lim}$	limiting inlet concentration of operation i ,ppm
$C_{i,out}^{\lim}$	limiting outlet concentration of operation i ,ppm
$C_{i,in}^{w}$	water supply inlet contaminant concentration of operation i ,ppm
$C_{i,out}^{w}$	water supply outlet contaminant concentration of operation i ,ppm
C_{in}^{w}	overall water supply contaminant concentration of operation i, ppm
C_{k}^{*}	contaminant concentration at interval boundary k, ppm
C_{pinch}^{*}	contaminant concentration at each pinch interval boundary, ppm
$f_{i}^{\lim}$	limiting flow rate ,tph
$f_{\min}$	overall minimum fresh water flow rate ,tph
$f_{\min,i}$	minimum fresh water flow rate for operation i ,tph
$\Delta m_{i,total}$	total contaminant mass load to be transferred from operation i, kg /h
Δm_{k}	contaminant mass load to be transferred below the pinch interval boundary, kg /h
Δm_{total}	total contaminant mass load transferred to all operation i, kg /hr
Δm_{pinch}	contaminant mass load transferred below the pinch interval boundary, kg /h
$f_{i,k}$	fresh water flow rate to process i in interval k ,tph
$f_{i,k}^{total}$	total water flow rate to process i in interval k ,tph
$m_{i,k}$	contaminant Mass load transferred in process i in interval k, kg /h
C_{o}	regeneration outlet concentration, ppm
C_{out}	average outlet concentration, ppm
C_{pinch}	fresh water pinch concentration, ppm
C_{regen}	regeneration inlet concentration, ppm
C_{pinch}^{*}	regenerated water pinch concentration, ppm

$f_i^{\lim}$	limiting flow rate, tph
$f_{\min,j}$	minimum flow rate for operation j , tph
$f_{recycle}$	recycle flow rate, tph
f_{regen}	regeneration flow rate, tph
$f_{unregen}$	flow rate of water not regenerated, tph
Δm_{regen}	mass load of contaminant transferred prior to regeneration, kg /h
Δm^*_{pinch}	mass load of contaminant transferred below the regenerated water pinch concentration, kg /h
N_{int}	number of mass intervals in the CID
N_o	number of operations,
i	number of operations
INR	Indian Rupees
REG	Regeneration unit
$C_{i,j,in}$	Limiting inlet concentration of contaminant J for operation i , ppm
$C_{i,j,n}$	Actual concentration of contaminant J in operation i at concentration interval boundary n, ppm
$C_{i,j,out}$	Limiting outlet concentration of contaminant J for operation i , ppm
$C^*_{i,in}$	Reference concentration at the inlet of operation i, ppm
$C^*_{i,n}$	Reference concentration at the outlet of operation i, ppm
f_i	Limiting flow rate of operation i, ppm
$F_{i,n}$	Fresh water flow rate to operation i at concentration interval boundary n , tph
$f^*_{i,n}$	The total flow rate to operation i at concentration interval boundary n, tph
$q_{li,m\le n}$	Reuse flow rate from operation l at concentration interval boundary n to operation i at concentration interval boundary n (m $\le$n), tph
$T_{i,n}$	Water flow rate available for reused within operation i at concentration interval boundary n , tph
$T_{i,n+1}$	Water flow rate available for reuse within operation i at concentration interval boundary n+1 , tph

$W_{lj,m\le n}$	Concentration of contaminant J in water available for reuse from operation l at concentration interval boundary m to operation J at concentration interval boundary n (m $\le$ n), tph
$W_{ij,n}$	Concentration of contaminant J in water available for reuse within operation i at concentration interval boundary n ,ppm
$W_{ij,n+1}$	Concentration of contaminant J in water available for reuse within operation i at concentration interval boundary n +1 ,ppm
$W_{avgij,n}$	Average Concentration of contaminant J in water available for reuse within operation i at concentration interval boundary n ,ppm

CHAPTER 1

INTRODUCTION

1.0 Necessity of water minimization

The rapid growth in population, coupled with industrialization and urbanization, has resulted in an increase in the demand for water leading to serious environment consequences. Several industrial processes, such as, stripping, liquid–liquid extraction and washing operations, among the many processes present in refineries and chemical plants, require extensive utilization of water. It may contain various hazardous or toxic pollutants that need to be strictly controlled. Apart from waste water generation, the amount of water used in manufacturing varies significantly from industry to industry as well as process to process. As a rough estimate, in chemical manufacturing, total process and cooling water usage is 0.0045-0.045 m^3 per kg of product. Scarcity of water and stringent regulations for industrial effluents has led to a paradigm shift in thinking about water usage. Further, the cost of water is becoming a significant factor in commodity material manufacturing. As water supply and treatment costs increase, there will be increasing pressure in the chemical process industries to reduce water consumption.

There are many types of technologies/methodologies available to save fresh water and reduce waste water generation. Water system integration, one of the important methodologies of wastewater minimization, treats the water utilization processes of an industry as an organic whole, and considers how to allocate the water quantity and quality to each water using unit, so that water reuse is maximized within the system and simultaneously the wastewater generation is minimized. This method shows excellent effectiveness in saving freshwater and reducing wastewater.

Therefore, much research has been devoted to the three approaches on water system integration, including water reuse, regeneration-reuse and regeneration- reuse-recycle. The developing field of water-pinch technology evolved out of the broader concept of process integration.

1.1 Process integration methods

Process Integration is a fairly new term that emerged in the 80's and has been extensively used in the 90's to describe certain systems oriented activities related primarily to process design. Process integration can be described as "*a holistic approach to process design, retrofitting, and operation which emphasizes the unity of the process*", differently to a design approach that optimizes at the unit operation level. Process integration enables the designer to see "*the big picture first, and the details later*". Based on this approach, it is not only possible to identify the optimal process development strategy for a given task, but also to uniquely identify the most cost-effective way to accomplish that task. The implementation of PI methods can lead to significant energy savings and waste reduction (primary wastewater minimization). Some of research centers reported that "*PI is probably the best approach that can be used to obtain significant energy and water savings as well as pollution reductions for different kind of industries*". This potential exceeded the results obtained by than traditional audits, based on separate optimization of individual process units. Today Process integration can be broadly categorized into mass integration and energy integration. Energy integration deals with the global allocation, generation, and exchange of energy throughout the process. Mass integration creates the picture of the global flow of mass within the process and optimizing the allocation, separation, and generation of streams and species. It has been developed and applied to the environmental and mass processing problems of the processes. A review of some process integration design tools for addressing energy conservation and waste reduction is provided in **Table 1**.

1.2 Objective of present study

1. To apply water pinch technology to determine water conservation opportunities in different sections of a Starch industry in the state of Gujarat, India. Four different case studies have been viewed as a single and multiple contaminant systems. The aims of study is to minimize the consumption of fresh & DM water and the production of wastewater and to design optimal targets for water use so that the plant's outdated water network could be updated, while accounting for current economic and technical restrictions.

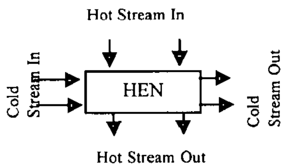
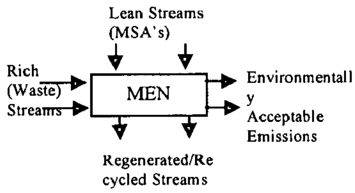
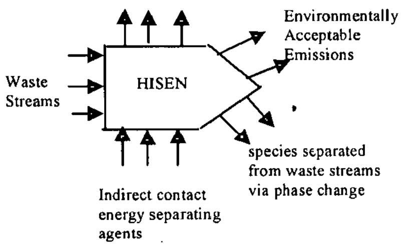
2. To apply graphical technique to solve different problems and establishment of graphical technique as easiest methods to prepare preliminary water minimization strategies.

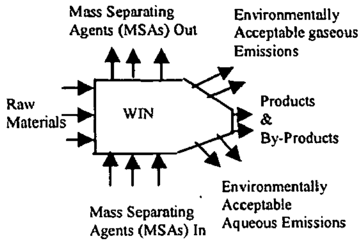
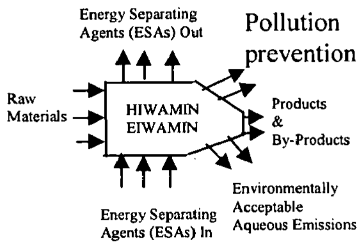
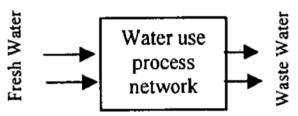
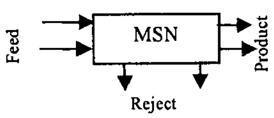
3. To compute detail cost benefits analysis and establish the potential of water pinch technology as one of the important source to govern economy of an industry.

4. To analyze potential of water conservation through energy management in a glass industry.

5. To develop MATLAB based computer program and excel based computational sheets for operation 1 to 5.

Table 1.1 Summary of Process Integration design tools

PI Methodology	Schematic Description	Short Description	Technology targeted
Heat Integration systems or Heat Exchanger Networks (HENs)		The identification of heat recovery options, devices that minimize environmental emissions resulting from utility generation systems.	(1)Heat Exchangers (2) Heat Pumps (3) Cooling towers
Mass Exchange Networks (MENs) and reactive mass exchange networks (REAMENs)		A network of process units that removes pollutants from end of pipe streams via the use of physical or chemical, direct contact, mass separating agents.(MSAs)	(1) Adsorption (2) Absorption (3)Liquid-Liquid Extraction (4) Ion Exchange
Heat Induced Separation networks(HISENs) and energy induced separation networks (EISENs)		A network of process units that removes pollutants from end of pipe streams via the use of indirect contact energy separating agents (ESAs), including stream pressurization and/or depressurization.	(1)Condensation (2) Evaporation (3)Drying (4) Crystallization (5)Compressors (6)Vacuum Pumps

In plant separation design via waste interpretation and allocation networks (WINs)		A network of process units that removes pollutants from end of pipe streams via the use of physical or reactive direct contact mass separating agents and/or rerouting of in-plant process streams.	(1)Direct recycle opportunities (2)Adsorption (3) Absorption (4)Ion-Exchange
In plant separation design via heat induced waste minimization networks (HIWAMINs) and energy induced waste minimization networks(EIWAMINs)		A network of process units that removes pollutants from in plant systems via the use of indirect –contact ESAs with stream pressurization and/or depressurization and/or rerouting of in-plant process streams. Full Site integration is addressed by this technique.	(1) Direct recycle opportunities (2) heat exchanger./ heat integration (3) Condensation (4) Evaporation
Waste water minimization problems		***A design strategy for reuse, regeneration reuse and regeneration-recycling of waste water streams that minimize water usage.***	***(1) Direct recycle Regeneration-reuse opportunities.***
Membrane networks separations		A network of process units that removes pollutants from end of pipe streams via the use of membranes.	(1) Reverse osmosis (2) Pervaporation

CHAPTER 2

LITERATURE REVIEW

This section begins by presenting brief outlines of the literature on the topic from several points of view (**Sections 2.1**), and then review in more detail approaches which were found to be particularly useful for the case studies involved in this project (**Sections 2.2**).

2.1 Concept of Water Pinch Technology

Three main uses of water in a manufacturing facility in chemical process industries are process uses, utility uses and other uses. **Fig.2.1** represents the most common water uses within a manufacturing facility in chemical process industries. Following preliminary water treatment, water is directed to (1) process uses, (2) utility uses and (3) other uses. **Fig.2.1** also illustrates common sources of waste water, including process uses, condensate losses, boiler blow down, cooling tower blow down and waste water from other uses such as storm-water runoff, housekeeping etc.

Conceptually, water pinch technology is a type of mass exchange integration involving water-using operations; it does not, involve the same practical problems that hinder the real world implementation of mass exchange networks, simply because the water-pinch technology represents existing class of manufacturing operations. It is a simple and practical model for representing the mass transfer of contaminants in water-using operations is the countercurrent contracting of a contaminant-rich process stream and a contaminant-lean water stream. This model provides the conceptual framework for analyzing, synthesizing, ad retrofitting water-using operations. As a result, water-pinch technology enables practicing engineers to answer a number of important questions when retrofitting existing facilities and designing new water-using networks in manufacturing processes.

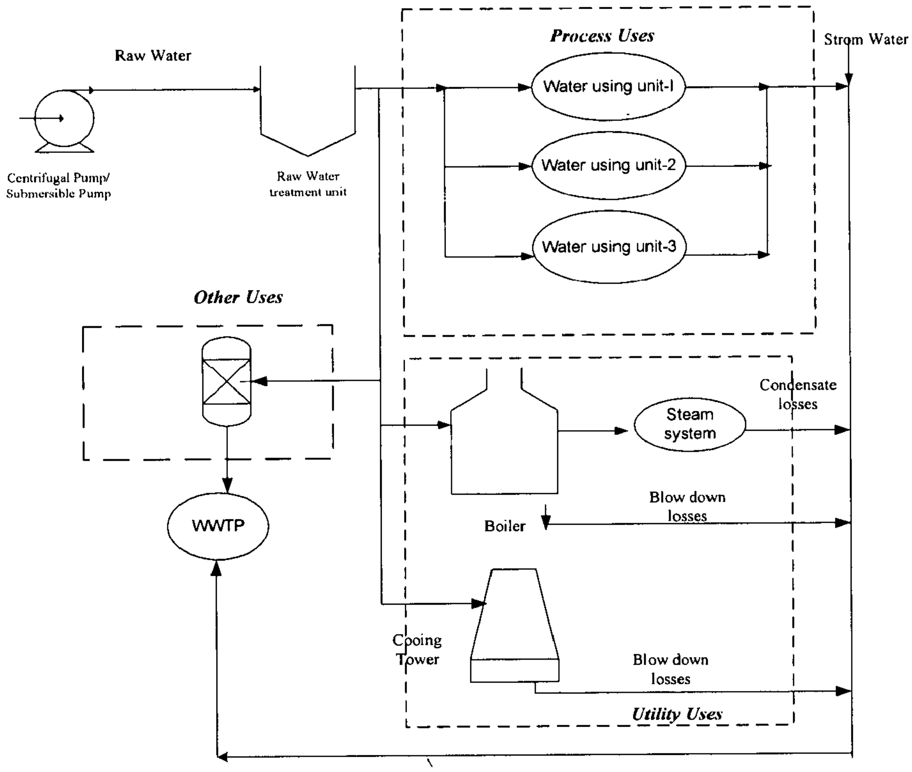


Fig. 2.1 Typical water uses in the chemical process industries: Process uses, utility uses, other uses (Smith, 1995b)

Those questions include:

(1) What are the maximum water-reuse target and the minimum waste water generation target for a manufacturing process?

(2) How do we design a new water-using network, or retrofit an existing network, to meet these targets?

(3) What is the minimum treatment-flow rate target in an effluent treatment system for a manufacturing process?

(4) How should we modify a manufacturing process to maximize water reuse and minimize waste water generation?

2.1.1 Strategies for industrial water reuse and Waste water minimization

The goals of conventional water-reuse projects are to reduce fresh water consumption, minimize effluent discharge, and achieve zero liquid discharge. The conventional approach to water reuse involves the following steps: (1) establishing the boundary limits for the project, (2) identifying water sources and sinks, (3) identifying and evaluating the factors that limit water reuse, and (4) preparing an engineering design and economic evaluation of a water-using network. Water –pinch technology can contribute significantly to the fourth step in conventional water-reuse design. The steps involved in applying water-pinch technology to industrial processes are (1) water use survey (2) data extraction, (3) targeting and design and (4) project economics and detailing. As shown in **Fig.2.2**, the solution strategy is divided into several steps to cover the various demands of the design problem.

2.2 Chronological Development of Water-pinch technology

The search for optimal wastewater reuse solutions was addressed by industry itself more than 28 years ago.

The hierarchy of methodologies used for the design of water reuse networks is much the same as that for retrofit designs aimed at waste minimization, these being as follows:

- Hierarchical design procedures
- Graphical techniques
- Mathematical programming approach

2.2.1 Hierarchical design procedures

Hierarchical design procedures consist of a series of heuristic rules, based on engineering knowledge and experience, aimed at screening process alternatives. Their usefulness has its limitations.

Liu (1999) presented a few interesting heuristic rules. Although some of them are incorrect, the solution procedure has remarkable simplicity and provides good sub-optimal (and sometimes optimal) solutions.

Zhi-Yong Liu *et.al* (2004) introduced a two-stage procedure is proposed for the minimization of wastewater. In the first stage, heuristic rules are used to find the initial feasible flow sheet; in the second stage, the flow rates of streams in the initial flow sheet are determined by mass balance of the contaminants.

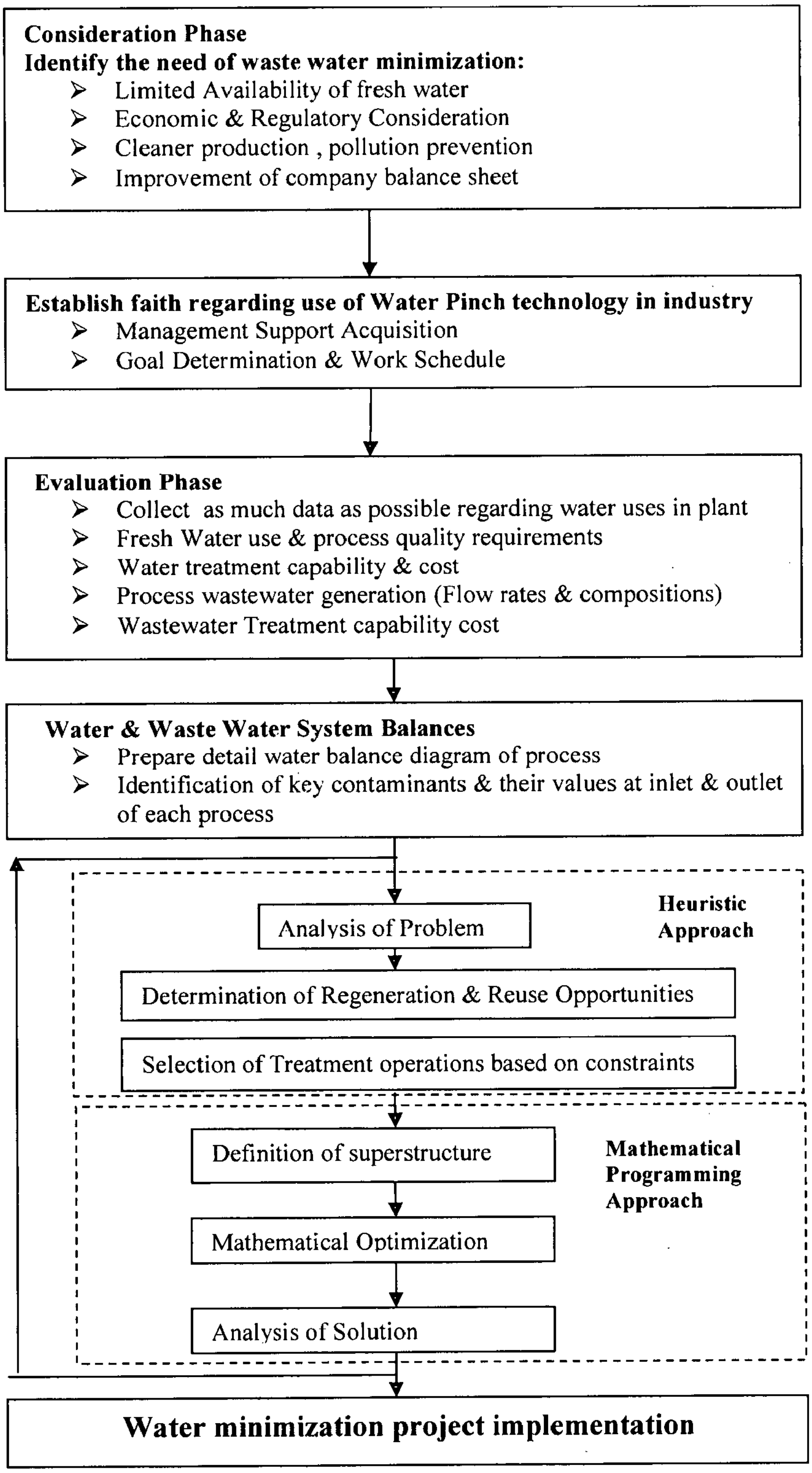


Fig. 2.2 Efficient approach of water minimization in chemical process industries

Gomes *et.al* (2007) presents a heuristic algorithmic procedure, water source diagram procedure (WSD), to synthesize water mass-exchange networks for the following different situations: (i) water reuse; (ii) availability of multiple external water sources in the industrial plant; (iii) water losses along the process; (iv) flow rate constraints; (v) regeneration before reuse in other operations; and (vi) regeneration followed by recycling.

2.2.2 Graphical techniques

Process synthesis systematically guides the designer in the rapid screening of the various process options in order to identify the optimum or near optimum design. It also allows the assessment of the design possibilities before detailed design is initiated. The first application of these new design techniques involved the conservation of energy through the optimization of heat exchanger networks. This has led to the development of Pinch Technology as applied to energy conservation. In the dissertation work, main emphasis has been given to graphical techniques and all the cases haves been solved with tools of graphical techniques.

2.2.3 Mathematical programming approach

Heuristic procedures and graphical methods offer the advantage that they do not require specialized computer software packages or computer programming. The techniques are however unlikely to produce the optimal water management solution when it comes to larger problems involving multiple contaminants. In addition, the economic aspects of the problem, which is usually the criteria against which the pinch problem is to be optimized, cannot be dealt with in much detail resulting in solutions, which appear good from a water-reuse perspective, but are costly to implement. Mathematical programming techniques offer greater flexibility in terms of problem size, number of contaminants and economic analysis of the problem, but these techniques are generally only accessible through computer packages that are often expensive and require some experience in order to use. The benefits of these packages are however that the water reuse strategy produced is more likely to be economically viable. The chronological development of graphical approach has been discussed in details in following section:

Linnhoff and Flower (1978)

- *Pinch analysis* was initially developed for the optimization of heat exchanger networks.
- The problem of synthesizing optimal heat exchanger networks was approached in two successive stages and the use of the *problem table* in the synthesis of heat exchanger networks was also presented.

Mason and Wardle (1979)

- Applied the proposed methodology to practical problems.
- The role of ΔT_{min} and the effect of the pinch point in the design of maximum energy recovery networks were further demonstrated.
- The optimum use of utilities, the determination of the minimum number of process units, the effect of stream splitting and cyclic networks, practical problem constraints as well as data modification were described in detail.

Linnhoff *et al.* (1983)

- A graphical approach was proposed in which a heat exchange system is represented by a plot of temperature as a function of enthalpy.
- The streams that require cooling generate the hot composite curve and those that require heating generate the cold composite curve.
- The cold composite curve is below the hot composite curve. The point at which these curves come in the closest contact is the point at which there is a minimum heat transfer driving force. This point is known as the pinch point. The pinch point is then used to find the minimum process requirement and then the optimal network design.

(A)

A

Linnhoff and Hindmarsh (1983)

- The design method was proposed which was based on the location of the pinch point. This method entailed splitting the problem into two distinct regions, namely the *above pinch* and *below pinch* regions. This methodology emphasized the significance of the pinch in heat exchanger network (HEN) design by the introduction of threshold problems.

In 1988-94, the analogies between heat conservation and wastewater minimization had been used by various people to extend the pinch concept to waste water minimization.

Wang and Smith (1994-95)

- They presented a conceptually based approach, in which targets are set that maximize water reuse. Both single and multi-contaminant cases were addressed, along with the identification of regeneration opportunities.
- Procedures were presented for the design of networks, which allow the minimum target to be achieved. In their methodology different minimum concentration differences can be allowed throughout the network, together with constraints due to corrosion limitations etc.
- A composite curve similar to the temperature enthalpy curves introduced in thermal pinch analysis. They then matched this composite curve to a straight line through the origin. This minimum water supply line touches the composite curve at a minimum of two points i.e. the origin and one other. The points other than the origin are known as the Pinch Points.

B

B

Wang and Smith (1994, 95)

- They presented two methods to achieve this minimum flow rate design. The first is referred to as the *maximum driving force method*, which uses concentration differences between the various streams to target the minimum flow rate. The second method is referred to as the *minimum number of water sources method* and uses load intervals.
- In each interval only enough water is used to maintain network feasibility, the remainder is bypassed and used later.
- They also considered the case where more than one contaminant is present and extended their methodology to deal with this situation. Apart from that, the implications of regeneration of wastewater were also considered.
- Wang and Smith (1994b) presented a conceptually based approach of designing of distributed effluent treatment plant.
- In a later paper, Wang and Smith (1995a) discussed single and multiple operations with fixed flow rate and processes with multiple sources of water of varying quality. Water loss in processes is also taken into account as well as the possibility of several sources of water of varying quality. New design rules allow novel water flow schemes to be developed based on local recycling and splitting of

Although this approach has been a major step in understanding water system design, it has several limitations.

C

C

Olesen and Polley (1997)

- They reviewed the procedures introduced by Wang and Smith concerning single contaminants.
- They introduced a new network designing procedure in which they classify operations into distinct types, each of which has distinct design implications. This method is based on the use of a load table, which tabulates the distribution of duties in the region of the pinch and the minimum water needs for each operation.
- They considered the case of simple reuse, water draws and regenerated water reuse.

Kuo and Smith (1998)

- They also recognized the complexity of the evolutionary design procedure proposed earlier by Wang and Smith (1994a).
- In an effort to simplify the previous method, the authors introduced a new graphical approach. In addition, they addressed the optimal allocation of fresh water in combination with the distribution of quality of the wastewater that is to be treated.
- The method consists on identifying the pockets that can be created by successively bending the water supply line upwards. The next step is to create a water 'main' at the end of each pocket and identify processes that should be fed by these mains.
- This method has some limitations. For example, when several processes below the pinch have maximum inlet concentration larger than zero, it is not quite simple to identify which process needs to be fed using fresh water first and to what process each wastewater has to be sent..

D

D

Savelski & Bagajewicz (1999 a,b, 2000 a

- They clarified the limitation of Kim and Smith work by introducing the concept of monotonicity in the process-to-process connections. In addition, Gómez, Savelski & Bagajewicz (2000) provided an algorithmic procedure to address this matter.

Mann and Liu (1999)

- They have found that when considering water regeneration recycling, some systems had another pinch point, regeneration pinch, which is higher than the normal pinch for freshwater targeting.
- How to determine the optimal regeneration concentration and whether the optimal regeneration concentration relates to the normal pinch concentration need further study.
- They also introduced graphical techniques to determine minimum water flow rate in case of multi contaminant systems.

Polley and Polley (2000)

- They noted that unless the correct stream mixing system is identified, the apparent targets could be substantially higher than the true minimum fresh water and wastewater flow rates.

Hallale N (2002)

- He introduced a new graphical targeting method for water minimization. The new approach is based upon a new representation of water composite curves and the concept of water surplus. This is used to construct a water surplus diagram, which is similar to the grand composite curve in heat pinch analysis.

E

E

Feng *et al* (2007)

- They introduced use of graphical method to determine the targets of single-contaminant regeneration recycling water systems, by analyzing the limiting composite curve of a single-contaminant water system.
- A method was proposed to construct the optimal water supply line for regeneration recycling.
- Accordingly the targets for regeneration recycling water systems were obtained. The targets in sequence are the minimum freshwater consumption (the minimum wastewater discharge), the minimum regenerated water flow rate, and the optimal regeneration concentration.
- The results showed that for a single-contaminant regeneration recycling water system, the minimum freshwater consumption is determined by the shape of the limiting composite curve below the post-regeneration concentration.
- The optimal regeneration concentration is defined as the minimum regeneration concentration at the minimum freshwater consumption and the corresponding minimum regenerated water flow rate.

Literature review: Simultaneous water and energy conservation through Water Pinch technology

Kim *et al.*(2001)

- They introduced a method for the design of effluent cooling water systems, focusing on reducing the temperature of the effluent stream, rather than the contamination level.

Kim and Smith (2001)

- They developed a technique which has been based on to analyze the regeneration of thermally contaminated water. They assess the cooling water system as a holistic entity.
- That is, the design and analysis of the cooling towers is done with consideration of the cooling water network. To optimize such a cooling water network, the network interactions must be defined and the relationships between them applied to the simultaneous design of each component.
- They suggested that a combined water and energy analysis should be used to investigate the interaction for the overall system. A cooling tower model was developed as well as a method for the design of cooling water systems that accounts for the interactions and process constraints.
- They also looked at the interactions between the cooling water network and the cooling tower performance. The main advantage of the cooling water system design technique is that it investigated the interactions between the cooling tower and the cooling water network.

A

Literature review: Simultaneous water and energy conservation through Water Pinch technology

(A)

Kim et al. (2002)

- They extended the cooling water network system to incorporate refrigeration systems.

Kim and Smith (2003)

- They used an automated approach to investigate the interactions between cooling tower performance and the cooling water network design. A retrofit design of cooling water systems with minimum pressure drop by using an automated approach was explored.
- Furthermore, Kim and Smith (2004) developed a design method aimed at the reduction of cooling water makeup.

Zhelev (2003, 2005)

- They developed a conceptual approach for resource management in industrial cooling systems.

Savulescu et al. (2005)

They also developed a design methodology for simultaneous energy and water management..

Table : 2.1 Summary of Literature review (Major Paper referred during dissertation work)

Sr No	Title of Paper	Authors	Aim	Brief Methodology	Results	R. N
1	The Pinch design methods for heat exchangers	B. Linnhoff and E.Hindmarsh	To develop a novel method of heat exchanger networks based on the location of pinch point.	The method was the first to combine sufficient simplicity to be used by hand with near certainty to identify "best" designs, even for large problems. "Best" designs feature the highest degree of energy recovery possible with a given number of capital items.	Pioneer work. This methodology emphasis the significance of pinch point in HEN design.	41
2	Optimal water allocation in a Petroleum refinery	N. Takama, T. Kuriyama, K. Shiroko and T. Umeda	To develop a method for solving the planning problem of optimal water allocation.	All the alternative systems were combined into an integrated system by employing structure variables or split ratios at the point where a water stream was split into more than two streams.	The method was applied here to a simple but practical problem of optimizing water allocation in a petroleum refinery.	5[illegible]
3	Wastewater Minimization	Wang and Smith	To develop methods to target and design for minimum wastewater for the above three cases.	To addresses the minimization of wastewater in the process industries. Targets were first set which maximize water re-use. The approach used allows individual process constraints relating to minimum mass transfer driving force, fouling, corrosion limitations, etc. to be easily incorporated. Both single and multiple contaminants were addressed. The multiple-contaminant case allows multiple constraints relating to the multiple contaminants to be allowed for. Water regeneration opportunities were also identified at the targeting stages which distinguish between re-use and recycling. Two simple design methods were presented which allow targets both with and without regeneration to be achieved in design. The first design procedure maximizes driving forces in individual processes whilst the second minimize the number of water sources for each process. The approach adopted was entirely conceptually based.	A method had been presented which allows both freshwater and wastewater to be minimized in a wide range of processes. This minimization was brought about through maximizing water re-use and the identification of regeneration opportunities. Targets were first set for freshwater, regeneration and wastewater flow rates using limiting water profiles. These profiles allow constraints due to minimum mass transfer driving forces, equipment fouling, corrosion limitations, etc. to be included in the problem formulation. Both single and multiple contaminants can be addressed.	6[illegible] 6[illegible] 6[illegible]
4	Waste water minimization with flow rate constraints	Wang and Smith	To address water and waste water minimization through water re-use where there are fixed flow rate constraints.	Water losses from operations and situations with multiple sources of fresh water with different quantities were considered.	The design methods allowed novel water flow schemes to be developed based on local recycling and splitting of operations.	6[illegible]

Sr No	Title of Paper	Authors	Aim	Brief Methodology	Results	Ref. No.
5	A multi-contaminant transhipment model for mass exchange networks and wastewater minimization problems	A. Alva-Arga´ez, A. Vallianatos, A. Kokossis	The paper combines insights from Water Pinch with mathematical programming. The approach applies to mass exchanger network and wastewater minimization problems. Its purpose was the development of targeting models at a conceptual stage where the process network was not yet developed.	For wastewater minimization, the concept of the limiting water profile was employed. The development of utility targets for multiple contaminants was developed as a mixed integer linear transshipment formulation that enables easy screening and scoping ahead of the network development.	A new conceptual model was presented for targeting minimum utility costs. The conceptual model takes the form of a multi-contaminant transshipment model, and was formulated as a mixed-integer linear programming problem. The targeting tools described in this paper allow the screening of options in an automated fashion and can be used to identify opportunities for a more efficient use of both water resources and mass separating agents in the process industries. It was also possible to generate alternative solutions that may result in different networks achieving the same target.	1
6	Design of water utilization systems in process plants with a single Contaminant	Mariano Savelski and, Miguel Bagajewicz	To illustrate necessary conditions of optimality for single component water-using networks in process plants.	These necessary conditions correspond to the optimal water allocation planning (WAP) problem that considers wastewater reuse on the basis of a single contaminant and where the objective was to minimize the total water intake. The conditions under which degenerate solutions were possible were also identified. Examples were discussed. A method that can be implemented by hand was also provided.	Necessary conditions of optimality in water allocation problems had been presented. These conditions state that optimal structures satisfy monotonicity of the outlet concentrations when one process sends its wastewater to another.	57
7	Design procedure for water/wastewater minimization: single contaminant	Juliana F.S. Gomes, Eduardo M. Queiroz, Fernando L.P. Pessoa*	A new methodology known as WSD had been proposed.	A heuristic algorithmic procedure, water source diagram procedure (WSD), to synthesize water mass-exchange networks for the different situations.	It was applied in a single contaminant example case, and it can easily be extended to multiple contaminant processes. This new procedure had advantageous features when compared to other available methodologies.	26

Sr No	Title of Paper	Authors	Aim	Brief Methodology	Results	Re. No
8	A new graphical targeting method for water Minimization	N. Hallale	To develop a new graphical method for targeting fresh water and wastewater minimization.	The new approach was based upon a new representation of water composite curves and the concept of water surplus. This was used to construct a water surplus diagram, which was similar to the grand composite curve in heat pinch analysis. The method had several advantages over existing techniques, such as being able to deal with a wider range of water-using operations as well as having more convenient and familiar representations. Also, the targets were unique and were not dependent on any assumed mixing arrangement. The paper briefly discusses network design and also considers two areas process modifications and water regeneration, where the insights obtained from the graphical tools were most valuable.	This paper had presented a new, graphical approach to targeting the minimum fresh water and wastewater flow rates for a system of water-using operations. only considered problems with one contaminant. Although experience had shown that good results can be often obtained by initially modeling problems as being single-contaminant systems, there may be cases where multiple-component considerations were important.	30
9	Design of cooling systems for effluent temperature reduction	Jin-Kuk Kim, Luciana Savulescu and Robin Smith	To introduces methods for the design of effluent cooling systems.	A new systematic method was introduced for the segregation strategy for effluents to deal with effluent temperature problems most effectively by a combination of heat recovery and effluent cooling. This can lead to distributed effluent cooling systems. The design procedure sets targets before design. A design procedure then allows the targets to be achieved by following design rules for distributed cooling. An optimization model had been developed to search for the most economic design of cooling systems.	A new approach based on distributed effluent cooling systems had been introduced to cope with problems of thermal pollution. Distributed cooling systems were optimized to target and design for effluent temperature reduction.	33
10	Studies on simultaneous energy and water minimization— Part I: Systems with no water re-use	Luciana Savulescu, Jin-Kuk Kim and Robin Smith	To develop new systematic methodology for targeting and design that simultaneously minimizes the requirements of energy and water.	Using this new approach, the design of a water system for maximum energy recovery can be achieved, taking into account the mixing opportunities offered by water networks, while maintaining the water quality to processes in terms of contamination. Direct and indirect energy recovery were analyzed and a strategy developed to decrease the number of heat transfer units based on the generation of separate systems and non-isothermal stream mixing. Initially, the analysis was restricted to no water re-use.	The new method provides the understanding for design problems in simultaneous water and energy minimization and had led to a systematic procedure that takes into account targets for efficient use of water and energy.	56 A

Sr No	Title of Paper	Authors	Aim	Brief Methodology	Results	
11	Studies on simultaneous energy and water minimization—Part II: Systems with maximum re-use of water	Luciana Savulescu, Jin-Kuk Kim and Robin Smith	To develop new systematic design methodology for the simultaneous management of energy and water systems that also feature maximum re-use of water.	A two-dimensional grid diagram was proposed to exploit different options within water systems and also enable reduced complexity of the energy and water network. Isothermal and non-isothermal stream mixing between water streams were introduced to create separate systems between hot and cold water streams in the energy composite curves and provide a design basis for a better structure with fewer units for the heat exchanger network. In addition to allowing re-use of water, issues about heat losses inside unit operations had also been incorporated in the simultaneous management of water and energy.	New design procedure had been developed to achieve both water and energy targets for systems using water at different temperatures and re-use of water. This procedure involves two stages. In the first stage, re-use options within the water system were exploited not only from the point of view of contaminant concentration, but also considering energy. A new grid representation (the two-dimensional grid diagram) had been introduced.	56 B
12	Book : Industrial water reuse and Waste water minimization	James Mann and Liu	Relatively easy to use and surprisingly inexpensive, the methods one find in this important guide - particularly water-pinch technology -is nc only ecologically sound, but significantly lower manufacturing costs. Concepts are illustrated with abundant charts, tables, and real-life cas studies.			
13	Cooling water system design	Jin-Kuk Kim and Robin Smith	To develop methodology for the design of cooling networks to satisfy any supply conditions for the cooling tower.	A model of cooling tower performance allows interactions between the performance of the cooling tower and the design of cooling water networks to be explored systematically. In debottlenecking situations, better design of the cooling network using the new method, including increasing cooling tower blow down, taking hot blow down and strategic use of air coolers, can all be used to avoid investment in new cooling tower capacity and to improve the performance of the cooling tower in a systematic way.	A mathematical model of cooling systems had been developed to predict the tower performance and to provide design guidelines for cooling water system design. A new methodology for the design of cooling water networks had been developed to satisfy any supply conditions for the cooling tower. Design can be carried out with any target temperature by introducing the concepts of pinch migration and temperature shift.	32

CHAPTER 3

PROBLEM STATEMENTS

[INDUSTRIAL CASE STUDIES]

In this Chapter, five water system design problems, which have been taken from different industries (mainly from starch and glass), are formulated which will be targeted and designed by graphical approach based on Water Pinch Technology.

3.1 *WATER MINIMIZATION IN STARCH PLANT*
Single Contaminant System (PROBLEM 3.1)

The detailed description of this problem is given in section **A.1 of appendix-A.**

Existing Network:

The Stream data is shown in the **Table 3.1** given below:

Table 3.1: Limiting Process Data for problem 3.1

Process	Max. Limiting Inlet Concentration $C_{i,in}$ (ppm)	Max. Limiting Outlet Concentration $C_{i,out}$ (ppm)	Limiting Flow Rate (tph)	Δm^i (kg/h)
FWM	1	20	120	2.28
S	10	40	140	4.20
SCR	20	300	100	28
GR	5	30	140	3.50

Required Results:

To design water-reuse network for this problem and make a benefit analysis of the selected water *reuse regeneration-reuse and regeneration-recycling* techniques. The solution of this problem is given in **section 5.1 of chapter 5**. The cost benefit analysis is shown in **section 6.2 of chapter 6.**

3.2 WATER MINIMIZATION IN STARCH PLANT
Single Contaminant System (PROBLEM 3.2)

The detailed description of this problem is given in section **A.2 of appendix-A.**

Existing Network:

The Stream data is shown in the **Table 3.2** given below:

Table 3.2 Limiting Process data for problem 3.2

Operation	**Limiting Water Flow rate f_i((tph)**	**Max. Limiting Inlet Concentration $C_{i,in}$ (ppm)**	**Max. Limiting Outlet Concentration $C_{i,out}$ (ppm)**
DM water using operations			
Primary Separators(PSI)	30	1 *	60
Primary Separators(PSII)	10	5	200
Process Reactor (R)	12	10	480
Dewatering section(DW)	12	15	350
Screen-4(S-4)	5	25	50

Required Results:

To design water-reuse network for this problem and make a benefit analysis of the selected water *reuse regeneration-reuse and regeneration-recycling* techniques. The solution of this problem is given in **section 5.2 of Chapter 5.** The cost benefit analysis is shown in **section 6.3 of chapter 6.**

3.3 *WATER MINIMIZATION IN GLUCOSE PLANT*

Single Contaminant System (PROBLEM 3.3)

The detailed description of this problem is given in section **A.3 of appendix-A.**

Existing Network:

The Stream data is shown in the **Table 3.3** given below:

Table 3.3 Limiting Process data for problem 3.3

Operation	**Limiting Water Flow rate f_i((tph)**	**Max. Limiting Inlet Concentration $C_{i,in}$ (ppm)**	**Max. Limiting Outlet Concentration $C_{i,out}$ (ppm)**
DM water using operations			
Operation 1	31	20	85
Operation 2	43	31	95
Operation 3	23	25	205
Operation 4	55	55	110
Operation 5	40	55	810
Operation 6	13	400	810
Operation 7	09	400	620
Operation 8	10	1	100
Operation 9	68	55	350
Operation 10	45	175	320

Required Results:

To design water-reuse network for this problem and make a benefit analysis of the selected water *reuse* technique. The solution of this problem is given in **section 5.3 of Chapter 5.** The cost benefit analysis is shown in **section 6.4 of chapter 6.**

3.4 WATER MINIMIZATION IN STARCH PLANT- Multicontaminant System (PROBLEM 3.4)

The detailed description of this problem is given in section **A.4 of appendix-A**.

Existing Network:

The Stream data is shown in the **Table 3.4 (a) & (b)** given below:

Table 3.4 (a) Limiting Process data for problem 3.4

Operation	**Contaminant Type**	**Limiting Water Flow rate f_i(tph)**	**Max. Limiting Inlet Concentration $C_{i,in}$ (ppm)**	**Max. Limiting Outlet Concentration $C_{i,out}$ (ppm)**
Reactor I(R-1)	Solids (TDS)	15	1	140
	Soluble(TSS)		7	105
	TOC(TOC)		2	15
Separators(S)	Solids (TDS)	15	1	205
	Soluble(TSS)		7	55
	TOC(TOC)		2	40
Grinding (G)	Solids (TDS)	10	1	410
	Soluble(TSS)		7	205
	TOC(TOC)		2	55
Washing (W)	Solids (TDS)	11	1	5
	Soluble(TSS)		7	10
	TOC(TOC)		2	5
Scrubbers(SCR)	Solids (TDS)	25	50	600
	Soluble(TSS)		220	230
	TOC(TOC)		30	35
Starch Washing Screens(SWS)	Solids (TDS)	30	50	70
	Soluble(TSS)		220	300
	TOC(TOC)		30	45
Cooling Tower I (CT-1)	Solids (TDS)	20	50	250
	Soluble(TSS)		220	1100
	TOC(TOC)		30	150
Cooling Tower II (CT-2)	Solids (TDS)	25	50	150
	Soluble(TSS)		220	660
	TOC(TOC)		30	90

Table 3.4 (b) The constraints associated with the water using networks.

Unit	Min. Water Flow rate (tph)	Max. Water flow rate (tph)	Min. Inlet Contaminant Concentration (ppm)			Max. Inlet Contaminant Concentration (ppm)			New Connections (After water pinch application)
			TDS	TSS	TOC	TDS	TSS	TOC	
Fresh Water	2	130	50	220	30	50	220	30	Allowed
DM Water	4	75	1	7	2	1	7	2	Allowed
R-1	15	15	1	7	2	5	7	5	Not allowed
S	15	15	1	7	2	5	7	5	Not allowed
G	5	10	5	7	2	25	100	15	Allowed
W	5	11	1	7	2	30	130	20	Allowed
SCR	20	30	50	220	30	200	210	50	Allowed
SWS	4	31	50	220	30	150	100	20	Allowed
CT1	8.5	8.5	50	220	30	475	300	100	Allowed
CT2	25	25	50	220	30	200	120	40	Allowed

Required Results:

To design water-reuse network for this problem and make a benefit analysis of the selected water *reuse* techniques. The solution of this problem is given in **section 5.4 of Chapter 5.** The cost benefit analysis is shown in **section 6.5 of chapter 6.**

3.5 WATER MINIMIZATION IN GLASS INDUSTRY

Cooling Tower system design (PROBLEM 3.5)

The detailed description of this problem is given in section **A.5 of appendix-A**.

Existing Network:

The Stream data is shown in the **Table 3.5** given below:

Required Results:

To design water-reuse network for this problem and make a benefit analysis of the selected cooling water network. The solution of this problem is given in **section 5.5 of Chapter 5.** The cost benefit analysis is shown in **section 6.6 of chapter 6.**

Table 3.5 Limiting process data for different sections of water using operations of a glass industry (Problem 3.5)

Equipment Description	Outlet Temp (⁰C)	Total Heat kW	Total Flow tph	Equipment Description	Outlet Temp (⁰C)	Total Heat kW	Total Flow tph
Furnace Melting Section							
Oil Burners with jacket(1.1)	41	586.04	100.8	Carbon Face (4.3)	37.5	6.279	3.6
Damwell (1.2)	39	83.72	24	Head Coolers (4.4)	40	781.387	168
Bubblers (1.3)	46	383.71	33	Down Stream Coolers (4.5)	40	948.827	204
Cameras of fusion end (1.4)	37	6.97	6	Down Stream Coolers (4.6)	40	1004.64	216
Bath Chargers Camera Top (1.5)	37	6.97	6	Banjo Coolers (Tin Bath Shoulder) (4.7)	40.5	376.74	72
Suspended Crown R/L Dog house (1.6)	37	11.16	9.6	Banjo Coolers (Tin Bath Exit) (4.8)	39	125.58	36
Flat Bridge R/L Dog House (1.7)	37	19.53	16.8	Radiation Pyrometers (Bay 3) (4.9)	37	1.395	1.2
Curtain Bridge R/L Dog house (1.8)	37	8.372	7.2	Radiation Pyrometers (Bay 5) (4.10)	37	1.395	1.2
Dust Cover R/L Dog House (1.9)	37	19.53	16.8	Radiation Pyrometers (Bay 7) (4.11)	37	1.395	1.2
				Radiation Pyrometers (Bay 13) (4.12)	37	1.395	1.2
Neck Section				Radiation Pyrometers (Bay 21) (4.13)	37	4.186	3.6
Waist Coolers (2.1)	43	781.38	96	Cameras at the hot end of tin bath (4.14)	37	3.488	3
Stirrer /Glass Homogenizer (2.2)	44	781.38	84	Cameras of top rollers (4.15)	42	52.325	9
				Cameras at tin bath (roof cameras) (4.16)	37	6.98	6
Refining & Spout Section				Cameras at tin bath exit (4.17)	37	3.49	3
Glass Level Measurement (3.1)	37.5	6.27	3.6	Cameras at tin bath end (4.18)	37	16.744	14.4
Spout Cut off box (3.2)	38.5	24.41	8.4	Tin Cooler sized Lift Out Rolls (4.19)	38.5	10.465	3.6
Spout Casing (3.3)	38.5	20.93	7.2	Empty lip casing (4.20)	37	48.84	42
TIN Bath Section				Exit lip casing (4.21)	40	29.30	8.4
Top rolls main CT (4.1)	38.5	87.20	30	Glass thickness measured (4.22)	40	4.186	1.2
Top rolls SCW (4.2)	39.5	195.34	48				

* Inlet temperature of cooling water = 36 ⁰C Cooling tower water supply temperature = 36 ⁰ C (Summer Season)
* Inlet temperature of cooling water = 32 ⁰C Cooling tower water supply temperature = 32 ⁰ C (Winter Season)

CHAPTER 4

SOLUTION TECHNIQUES IMPLEMENTED

In this dissertation, a number water pinch investigations were undertaken at industrial sites in order to promote the concept to Indian industries and to build local capacity to use it effectively. In this chapter an attempt is made to distil the lessons learned into a guide which will assist someone who wishes to conduct such an investigation. **Fig.4.1** represents the stepwise approach to tackle water minimization problems at industry level.

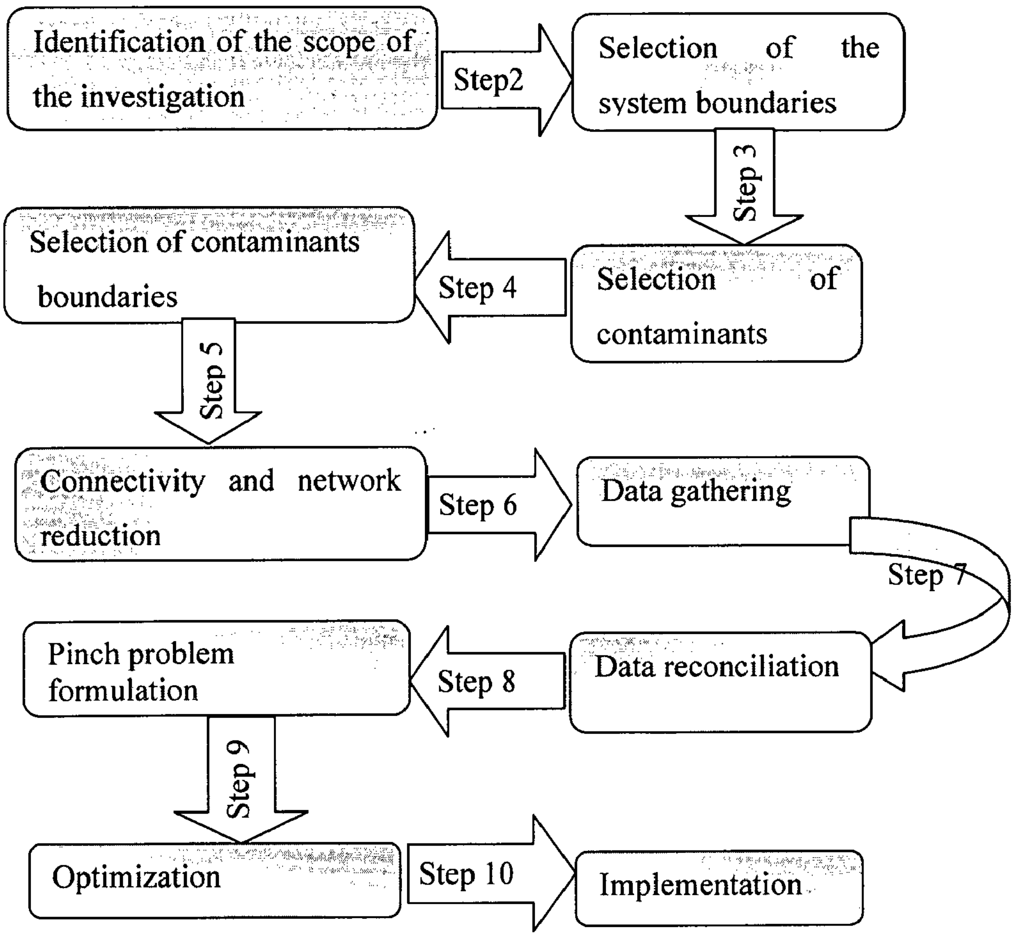


Fig. 4.1 Stepwise approach to tackle water minimization problems

It is seldom possible to proceed in a neat linear fashion through these steps, as later steps may expose issues which require earlier ones to be revisited. Furthermore, despite water pinch analysis being a rigorous and technical approach towards the rationalization of freshwater use and effluent production within a factory, the success or failure of the investigation relies heavily on the interactions between people of the investigation.

4.1 SOLUTION TECHNIQUES

Once the pinch problem has been formulated, a number of techniques are available which can be used to solve the problem. These techniques may be divided into three categories - heuristic procedures, graphical methods and mathematical programming techniques. The hierarchy of solution methods is as follows: heuristic procedures, graphical methods and mathematical programming techniques. Heuristic procedures and graphical methods offer the advantage that they do not require specialized computer software packages or computer programming. The techniques are however unlikely to produce the optimal water management solution when it comes to larger problems involving multiple contaminants. In addition, the economic aspects of the problem, which is usually the criteria against which the pinch problem is to be optimized, cannot be dealt with in much detail resulting in solutions which appear good from a water-reuse perspective, but are costly to implement. Mathematical programming techniques offer greater flexibility in terms of problem size, number of contaminants and economic analysis of the problem, but these techniques are generally only accessible through computer packages which are often expensive and require some experience in order to use. The benefits of these packages are however that the water reuse strategy produced is more likely to be economically viable. Different approaches are used in this dissertation to solve different real world case studies. These approaches are discussed in this chapter in detail as outline below:

(1) Approach of Wang and Smith(1994,1995) (Single Contaminant System-Graphical techniques
(2) Approach of Maan and Liu (1999) (Multi Contaminant System-Graphical and Mathematical Programming Approach)
(3) Approach of Kim and Smith(2001)(Water conservation through energy management)

4.2. Approach of Wang and Smith (1994, 1995)

This series of papers has been very influential in shaping the theory of water pinch analysis. There are four general approaches to waste water minimization (Wang and Smith, 1994):

(i) Re-use:

Wastewater can be re-used directly in other operations providing the level of previous contamination does not interfere with the process. Re-use might require wastewater being blended with wastewater from other operations and/or freshwater. (Note that there may be recycling within an individual operation but here we consider only the net input and output from operations.)

(ii) *Regeneration re-uses:*

Wastewater can be regenerated by partial treatment to remove the contaminants, which would otherwise prevent its re-use, and then re-used in other operations. Again, re-use after regeneration might require blending with wastewater from other operations and/or freshwater. Let us emphasize that when water is re-used after regeneration, in this case it does not re-enter processes in which it has previously been used.

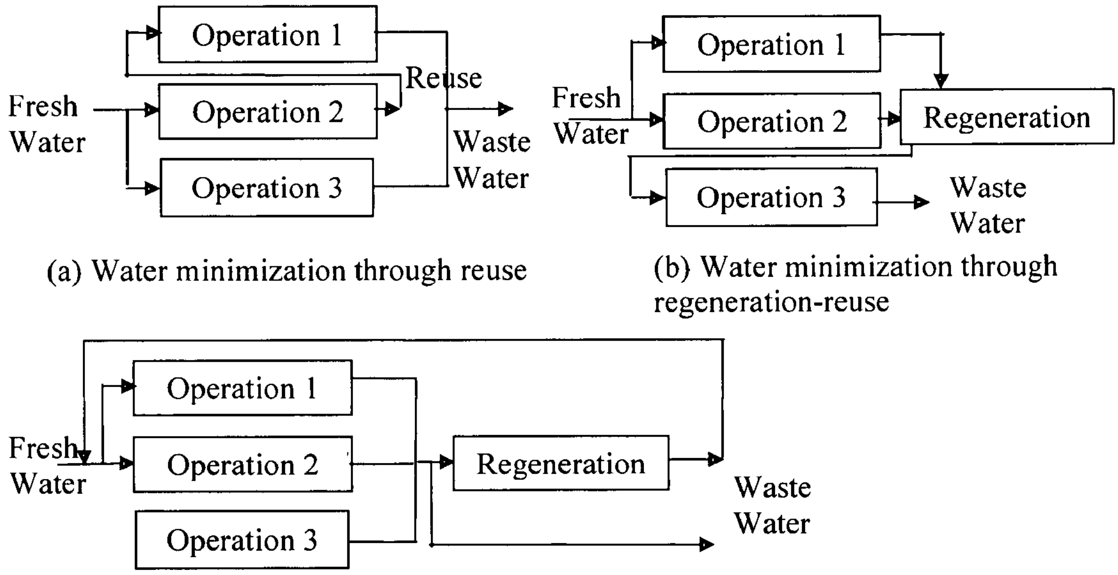
(iii) *Regeneration recycling:*

Wastewater can be regenerated to remove contaminants which have built up and then the water recycled. In this case water can re-enter processes in which it has previously been used.

(iv) *Process Changes:*

Process Changes can reduce the inherent demand of water.

Fig. 4.2 (a) to (c) represents the schematic representation of three approaches of water Pinch technology [Smith, 1995].



(a) Water minimization through reuse

(b) Water minimization through regeneration-reuse

(c) Water minimization through regeneration-recycle

Fig 4.2 Schematic diagram explaining different approaches for water minimization

4.2.1 Solution Methodology

In this section of the chapter, the solution technique required for waste water minimization problems is discussed. **Fig.4.3** represents the pre-selection strategically approach to solve water minimization problems using different approaches. Since this dissertation report considers only retrofitting problems and hence approach of process changes is not considered to obtain the modified water networks. The stepwise procedure is presented in **Fig. 4.4**. The first step is to identify potential water consuming operations along with stream data including constraints for different water using operations. The next step is to analyze the system without any water reuse. And then different approaches of water pinch technology such as *reuse, regeneration-reuse and regeneration-recycling* should be investigated. For the water reuse, feasibility of reuse of water from one water using operation to other has been identified and necessary water requirement is to be estimated. In second approach of regeneration-reuse, additional equipments for regeneration are used to regenerate waste water from water using operation. Then distribution of regenerated water is carried out for other water using operations. If recycling of water within operation is feasible then case has been considered as regeneration-recycling. The above approaches are discussed step wise in detail:

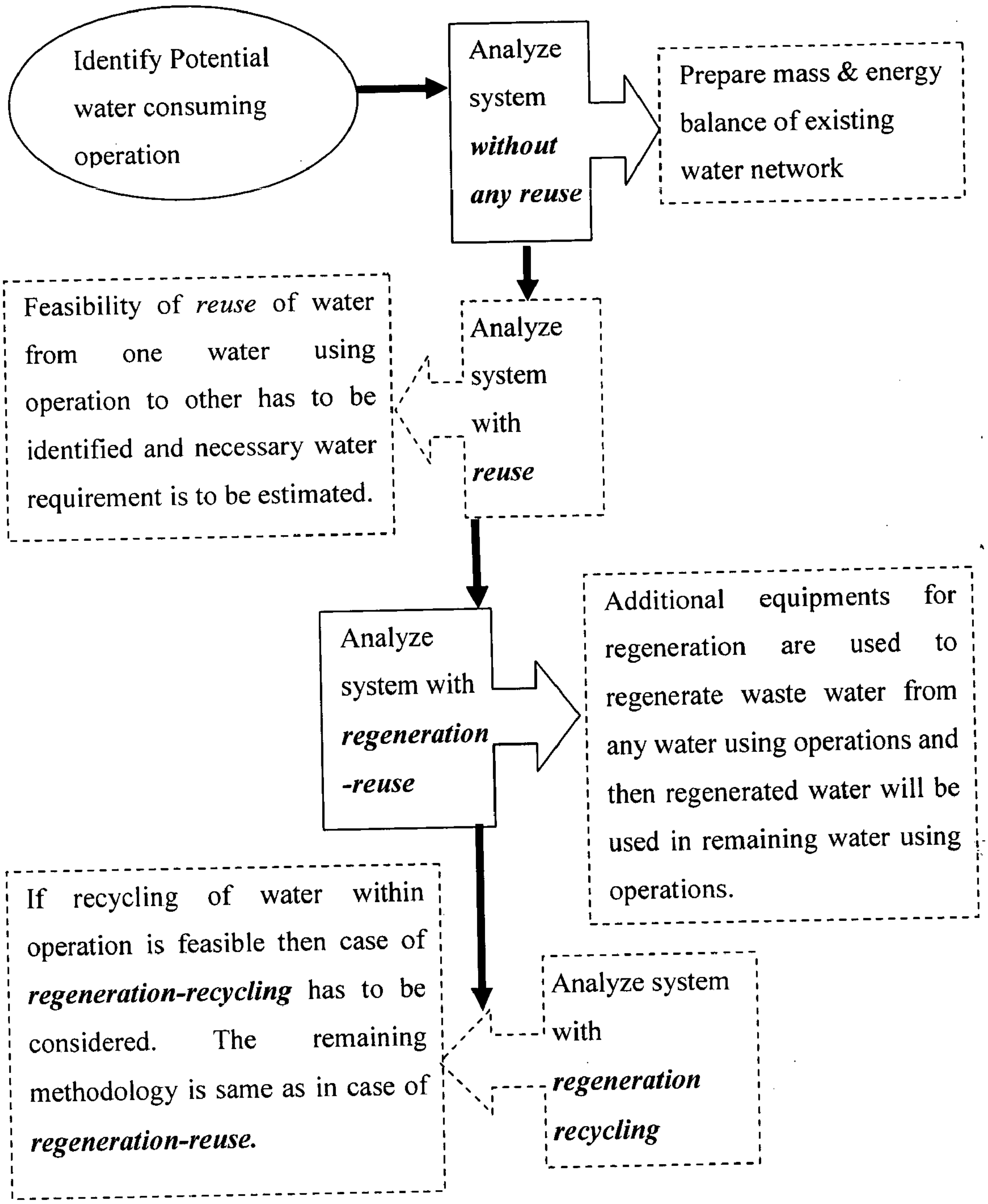


Fig. 4.3 Pre selection strategies for different approaches to solve water minimization problems

Step 1
Data Extraction

(A) Effectively extract stream data from water using operations.
(B) Define Inlet and Outlet streams.
(C) Identify the constraints of water using operations
(D) Determination of *limiting water flow rate,* based on above constraints. The *limiting water flow rate* for operation *i*

$$f_i^{\lim} = \frac{\Delta m_{i,tot}}{[C_{i\,out}^{\lim} - C_{i\,in}^{\lim}]} * 1000 \qquad ..(4.1)$$

Step 2
Limiting water profile

(A) A plot of contaminant concentration versus mass load for a given set of constraints for water using operation.
(B) Useful to identify the minimum limiting fresh water flow rate.
(C) **Fig 4.5** shows a general relationships between the limiting water profile and water supply line for operation *i*.
(D) $C_{i,\text{supply}}^{\text{w}}$ and $C_{i,\text{out}}^{\text{w}}$ are the contaminant concentration of the fresh water supply and the contaminant concentration of the water stream leaving operation *i*, respectively. There is an inverse relationship between the water flow rate for operation i , f_i and the slope of the water supply line as: $\frac{\Delta C_i}{\Delta m_{total}}$.

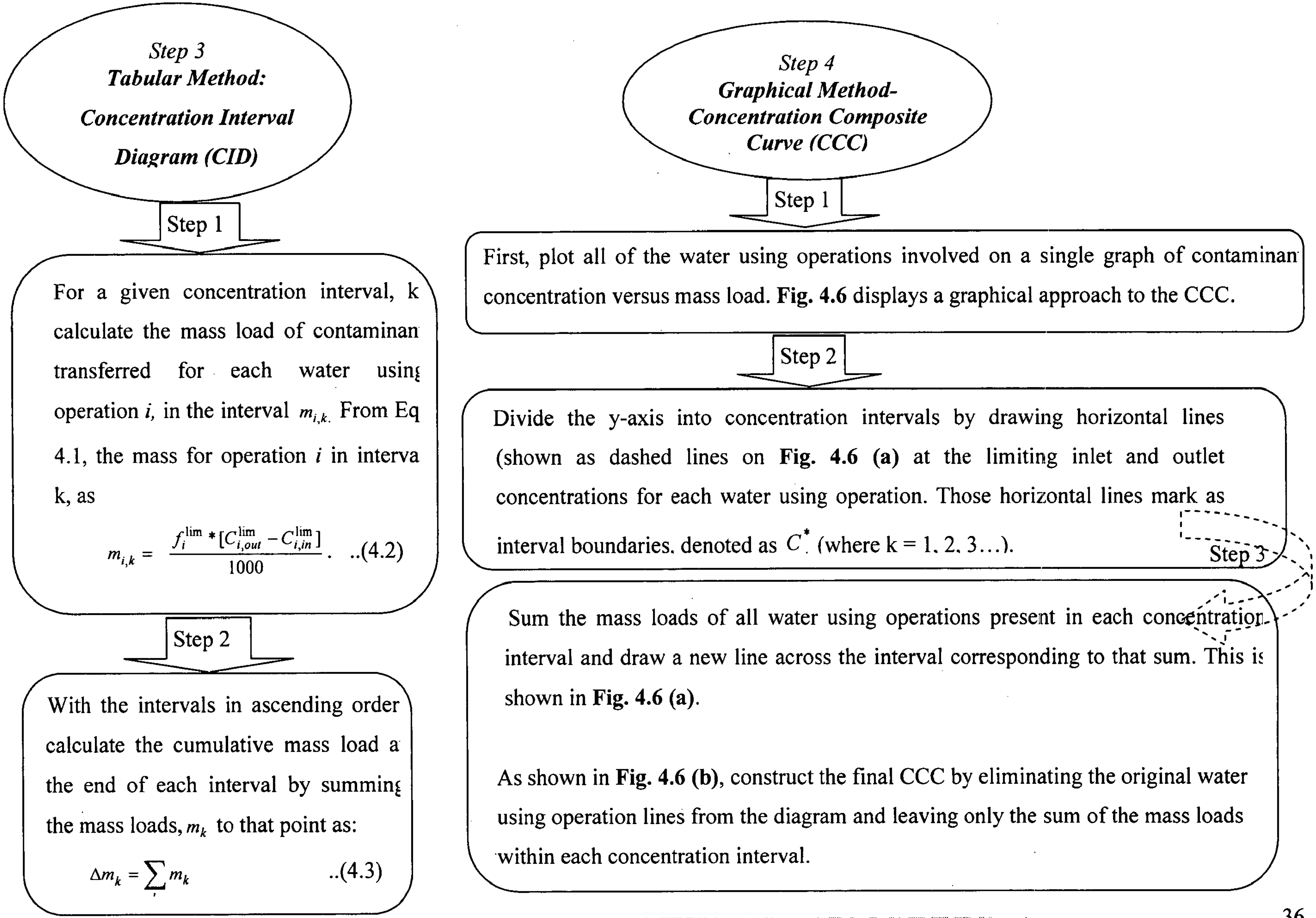


Fig 4.4 Stepwise procedure to solve water minimization problems using graphical technique

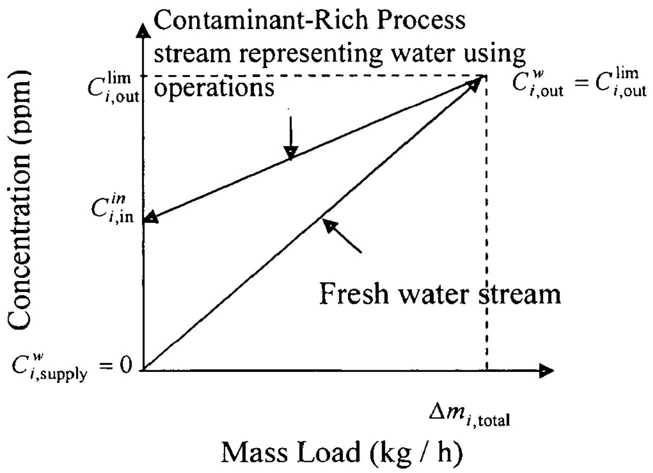


Fig. 4.5 The relationship between the limiting water profile and the water supply line

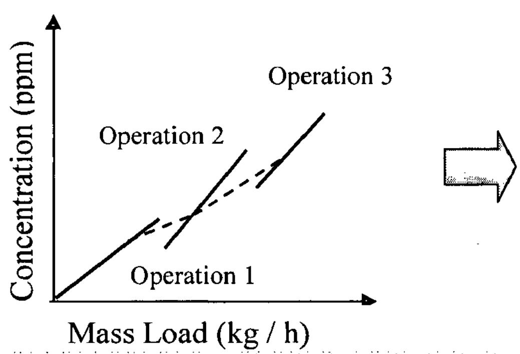


Fig.4.6 (a) Graphical approach to construct CCC

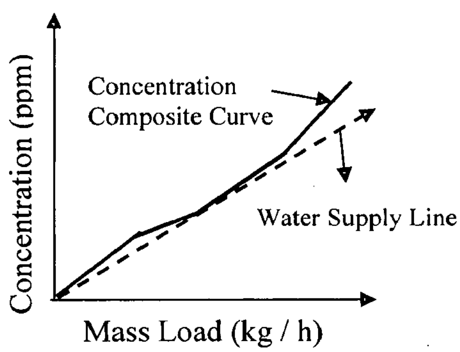


Fig.4.6 (b) CCC

Once the CCC has been established, the minimum fresh water flow rate can be obtained by drawing the water supply line on the CCC curve as shown in **Fig. 4.6 (b).** A MATLAB program is developed to generate CID and CCC. The programming code and necessary algorithm is shown in APPENDIX C.

4.2.2 Regeneration-reuse technique

The concept of *regeneration reuse* is divided in to four categories depending on water-using operations and is discussed in different sections. These are, *full regeneration & fresh water pinch, partial regeneration & regenerated water pinch, full regeneration & regenerated water pinch* and *Partial regeneration & fresh* *water pinch.* The first category *,full regeneration & fresh water pinch* refers to a process that increases the opportunities for water reuse through regeneration of all streams once these reach the optimal regeneration concentrations. All streams enter the regeneration process at the concentration of C_{regen} & this concentration is reduced to the minimum outlet concentration C_o. The second category uses the concept of *partial regeneration & regenerated water pinch,* when it is not possible to use full regeneration due to driving force violation that prevents the mass transfer of the contaminant from the water-using-operation to the fresh water. In some cases, the use of regenerated water may cause a portion of the CCC to lie below the regenerated water stream line. In this scenario the use of *full regeneration & regenerated water pinch* is recommended. The fourth category *Partial regeneration & regenerated water pinch is* used where full regeneration is impossible as the CCC falls below the regeneration concentration.

(A) Full Regeneration & fresh water pinch

Full regeneration refers to a process that increases the opportunities for water reuse through regeneration of all streams once they reach the optimal regeneration concentration. All the streams enter the regeneration process at a concentration of C_{regen}.This concentration is reduced to the minimum outlet concentration of the regeneration process $C_{o.}$ All streams exit at the same flow rate. The flow rate is constant before and after regeneration. In this thesis, the water stream prior to regeneration is referred as fresh water stream and water stream after regeneration process, is referred as regenerated water streams. Wang and Smith (1994) concluded that, for simple regeneration problems, the optimal regeneration concentration is the fresh water pinch concentration. **Fig. 4.7 (a) to (c)** explains three different scenarios when streams are regenerated below, above and at fresh water pinch concentration. To determine the optimal fresh water flow rate while keeping the regeneration concentration constant at the fresh water pinch concentration, the mass loads of contaminant labeled as "A", "B" and "C" in **Fig. 4.7(d)** are added and transferred to water stream which together forms the fresh water supply. The detail computational steps are shown in **Fig. 4.14 (a). Fig.4.7 (d)** also represents the CCC when full regeneration with fresh water pinch is applied.

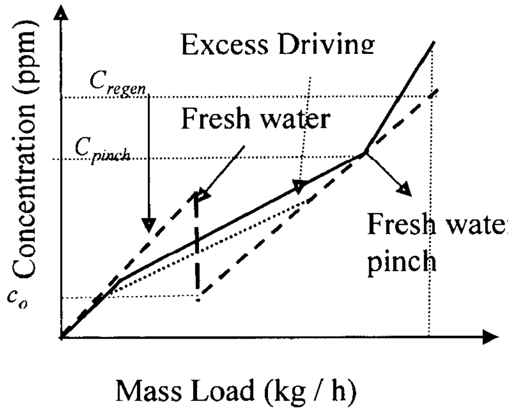


Fig. 4.7 (a) CCC for regenerating below fresh water pinch concentration

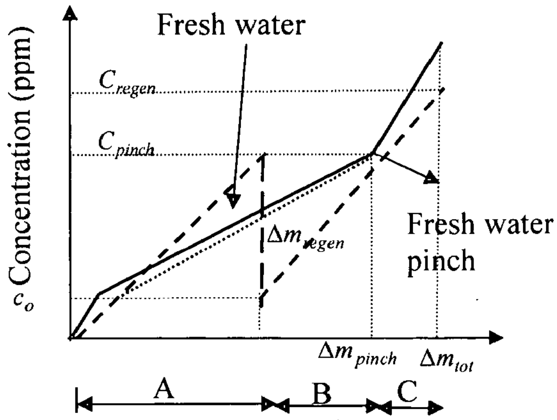


Fig. 4.7 (d) General CCC employing full regeneration

Composite water supply line

Regeneration Process

Regenerated Water, f_{regen}

Unregenerated Water, $f_{unregen}$

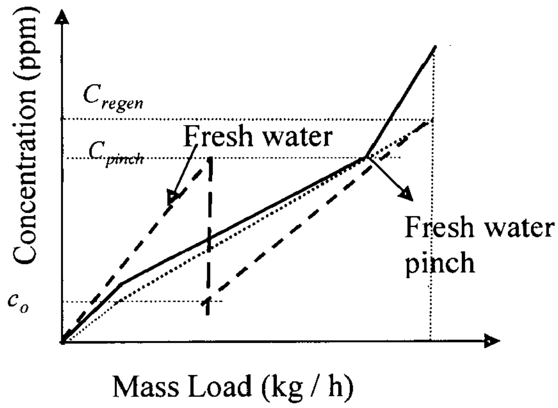


Fig. 4.7 (b) CCC for regenerating above fresh water pinch

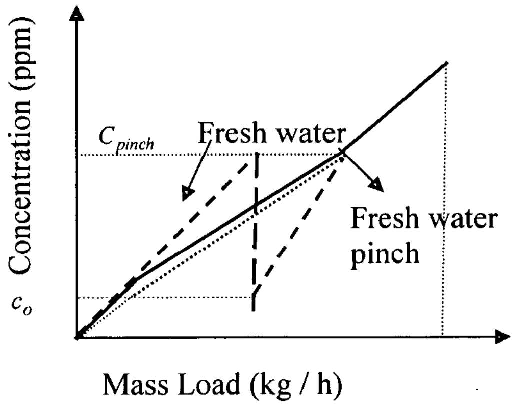


Fig. 4.7 (c) CCC for regenerating at fresh water pinch concentration

(B) Partial Regeneration and Fresh water pinch

In some cases, the shape of the portion of the CCC below the regeneration concentration may influence the targeted minimum flow rate of fresh water. As shown in **Fig. 4.8 (a),** CCC employing a full regeneration process creates a driving force violation that prevents mass transfer of the contaminants. For such cases, enough fresh water is to be supplied, to achieve the contaminant removal below c_o, the region below c_o has been treated as separate problem. If the water stream at the pinch concentration has been fully regenerated at the pinch concentration, then excess driving force is available as shown in **Fig. 4.8(b).** This excess driving force allows reducing the cost of regeneration process by partially regenerating water stream. **Fig.4.8 (c)** is a general CCC when partial regeneration is optimal. The flow rate of water to be regenerated is determined by the concentration interval between c_o and the pinch concentration. The detail computational steps are shown in **Fig. 4.14 (a).**

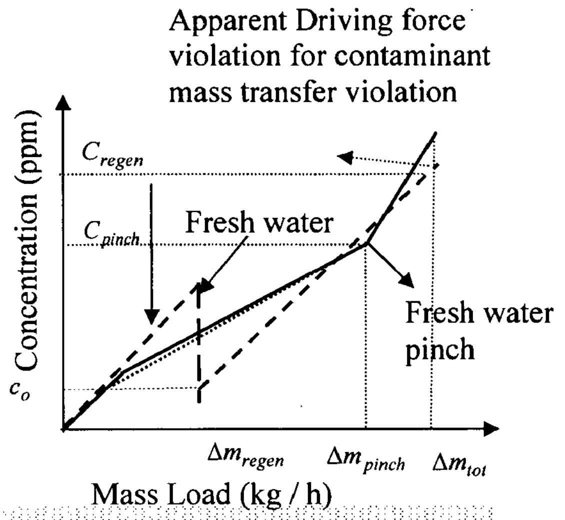


Fig. 4.8 (a) CCC employing full regeneration that creates driving force violation

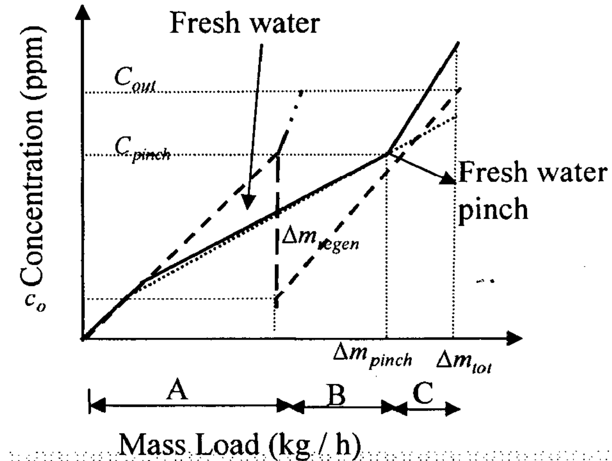
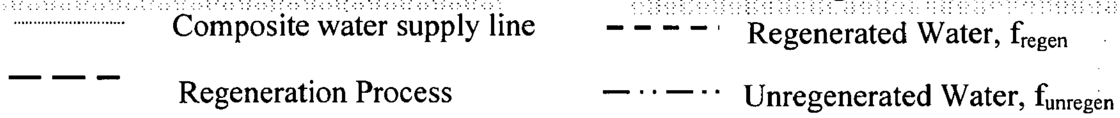


Fig. 4.8 (c) CCC requiring partial regeneration



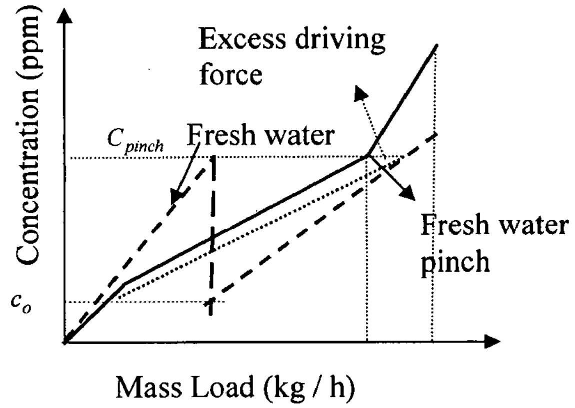


Fig. 4.8 (b) CCC employing full regeneration creating excess driving force

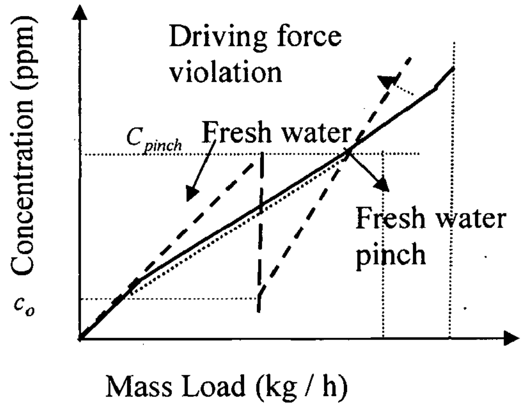


Fig. 4.9 (a) CCC with full regeneration at the fresh water pinch concentration

(C) Full Regeneration & regenerated water pinch

In some cases, the use of regenerated water may cause a portion of the CCC above the fresh water pinch to lie below the regenerated water stream. Here, fresh water pinch has been referred as the pinch point created when fresh water is used and regeneration in not allowed. **Fig.4.9(a)** represents the CCC & water supply lines with full regeneration, at the fresh water pinch concentration, it can be seen that a driving force violation above fresh water pinch concentration occur. To eliminate this driving force violation, the fresh water flow rate increases until the regenerated water stream just intersects the CCC above the fresh water pinch. This intersection point represents a new pinch, called the regenerated water pinch. **Fig.4.9 (b)** represents CCC and water supply line with full regeneration and regenerated water pinch concentration. The detail computational steps are shown in **Fig. 4.14 (b)**

(D) Partial Regeneration & fresh water pinch

As discussed in case of (C), where full regeneration is impossible due to the shape of the CCC below the regeneration concentration, greater flow rate of fresh water will be required. It also requires to partially regenerating the fresh water stream. However, in some cases there will be a possibility of driving force violation as shown in **Fig.4.10**. In such cases, regeneration flow rate is required to increase to eliminate a driving force violation above the fresh water pinch concentration.

As shown in **Fig. 4.11**, the fresh water stream, at a flow rate $f_{\min}$, is regenerated from the fresh water pinch concentration to the regeneration outlet concentration. The regeneration flow rate f_{regen} is just sufficient to the cause a regenerated water pinch, at C^{*}_{pinch} and Δm^{*}_{pinch}, above the fresh water pinch concentration. The flow rate of the unregenerated portion of fresh water stream is $f_{unregen}$. The detail computational steps are shown in **Fig. 4.14 (b).**

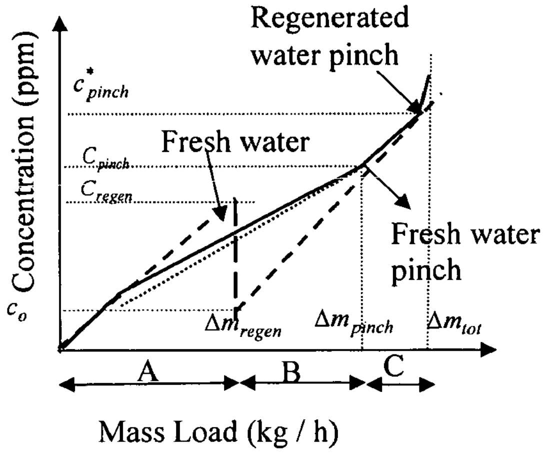


Fig. 4.9 (b) CCC (Full regeneration and regenerated water pinch)

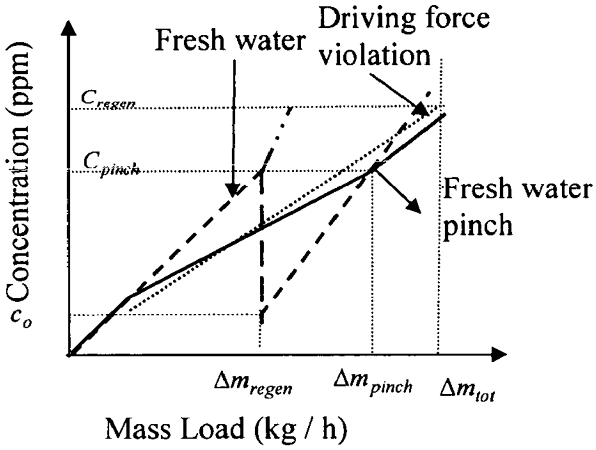
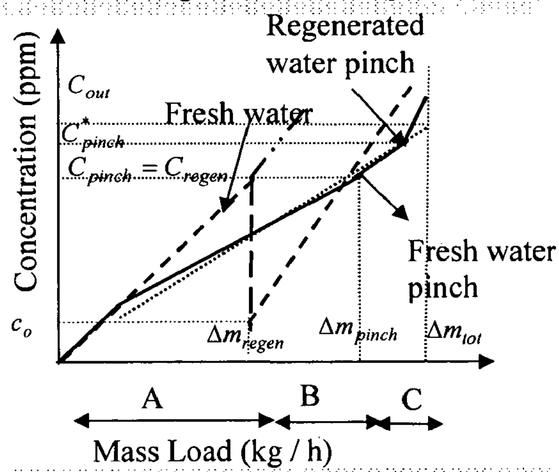


Fig. 4.10 Partial regeneration and driving force violation at fresh water pinch concentration



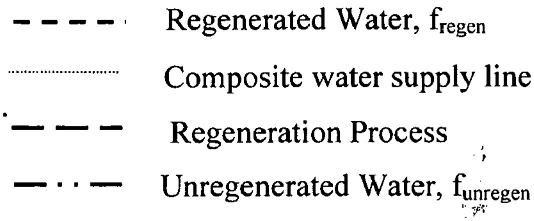


Fig. 4.11 General CCC and water supply line when partial regeneration creates regenerated water pinch

4.2.3 Regeneration-Recycling technique

Fig 4.12 illustrates a water using network with *regeneration recycle*. **Fig.4.13 (a)** represents a general CCC and optimal water supply line when regeneration recycle is allowed. The fresh water flow rate continues at a flow rate, $f_{\min}$, to the fresh water pinch concentration $C_{regen} = C_{pinch}$, prior to regenerating to the regeneration outlet concentration, C_o. With recycle it is possible to supply a wide range of flow rates of regenerated water to the region above the regeneration outlet concentration.

This recycle flow rate can be larger than the minimum fresh water flow rate that is determined by the CCC in the region below C_o .The regenerated water flow rate to be selected exactly equal to that required to pinch at the fresh water pinch.

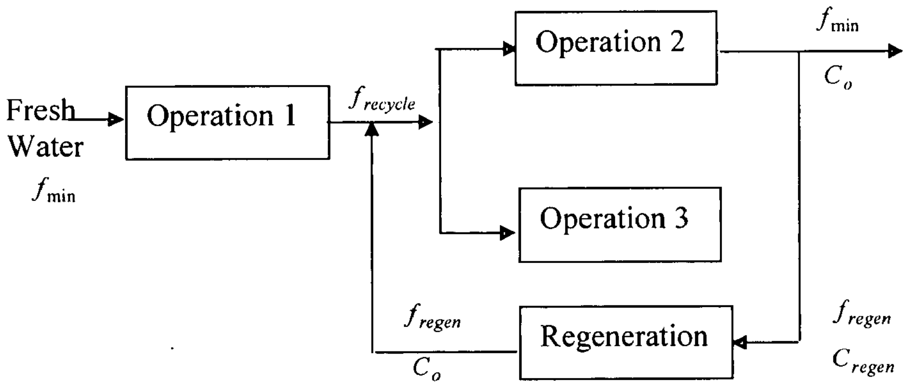


Fig. 4.12 Water using network with Regeneration-recycle

(A) Regeneration-recycling and regenerated water pinch

Fig. 4.13(b) represents a general CCC where regeneration recycle causes a regenerated water pinch. In the figure, the regeneration flow rate is chosen to create a regenerated water pinch above the fresh water pinch. The detail computational steps are shown in **Fig. 4.15**.

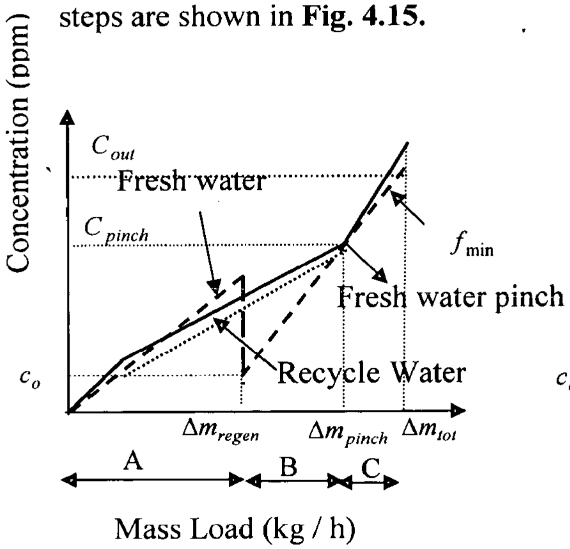


Fig. 4.13(a) General CCC and water supply lines (Regeneration-recycling)

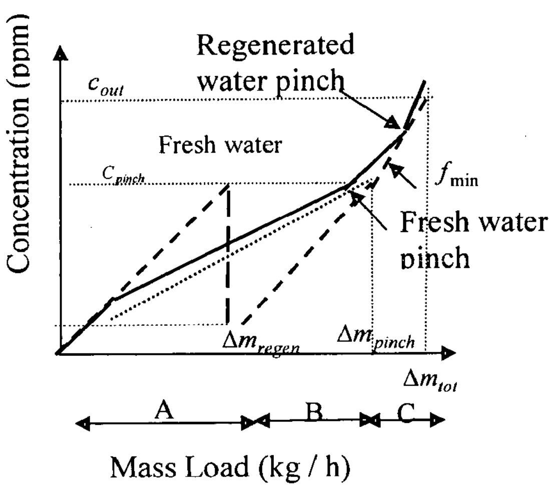


Fig. 4.13(b) General CCC and water supply line (Regeneration-recycling and regenerated water pinch)

- - - - Regenerated Water, f_{regen}

— — - Regeneration Process

.... Composite water supply line

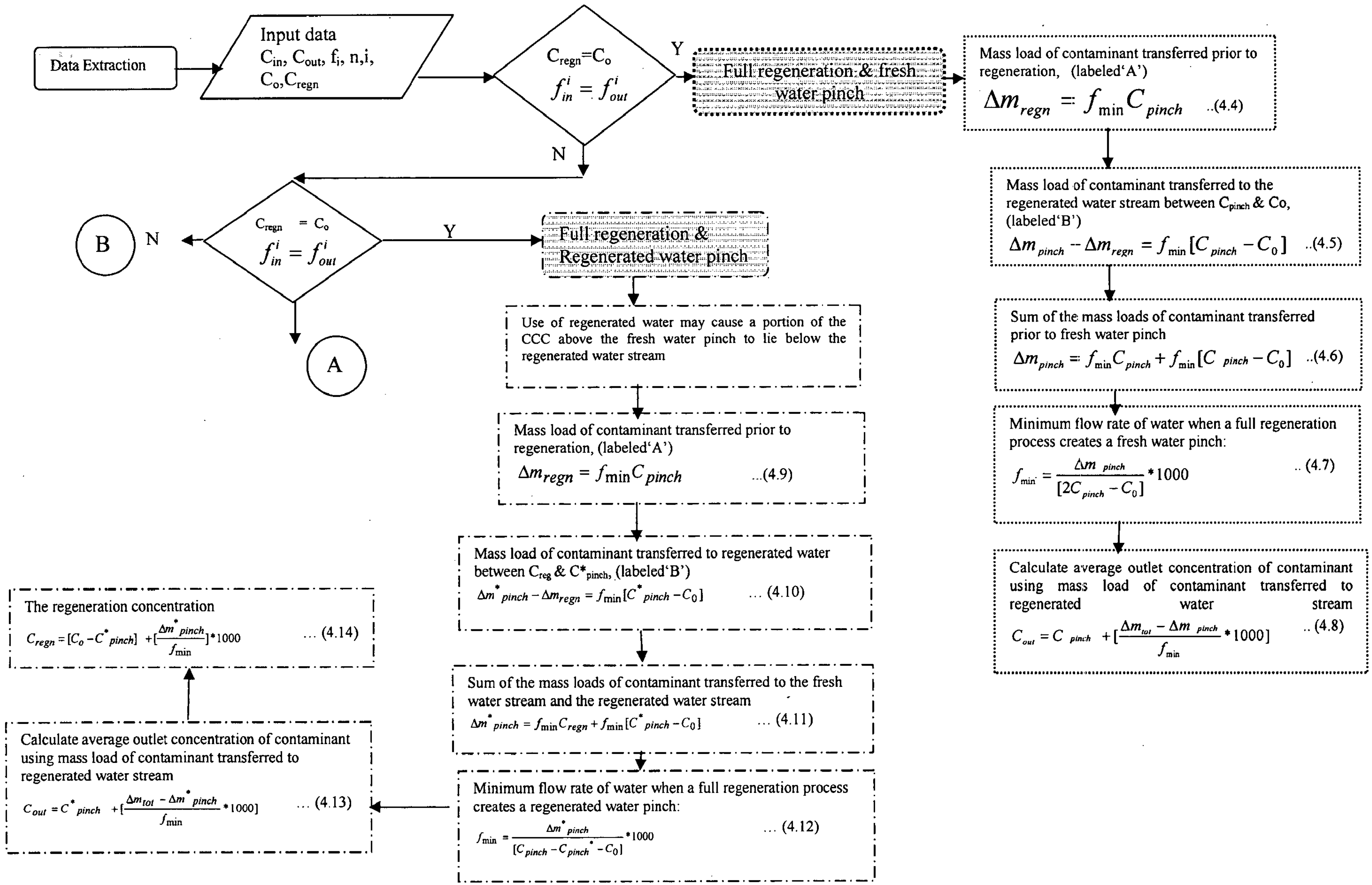


Fig. 14(a) Algorithm for different regeneration approaches (Full regeneration and fresh water pinch and full regeneration and regenerated water pinch

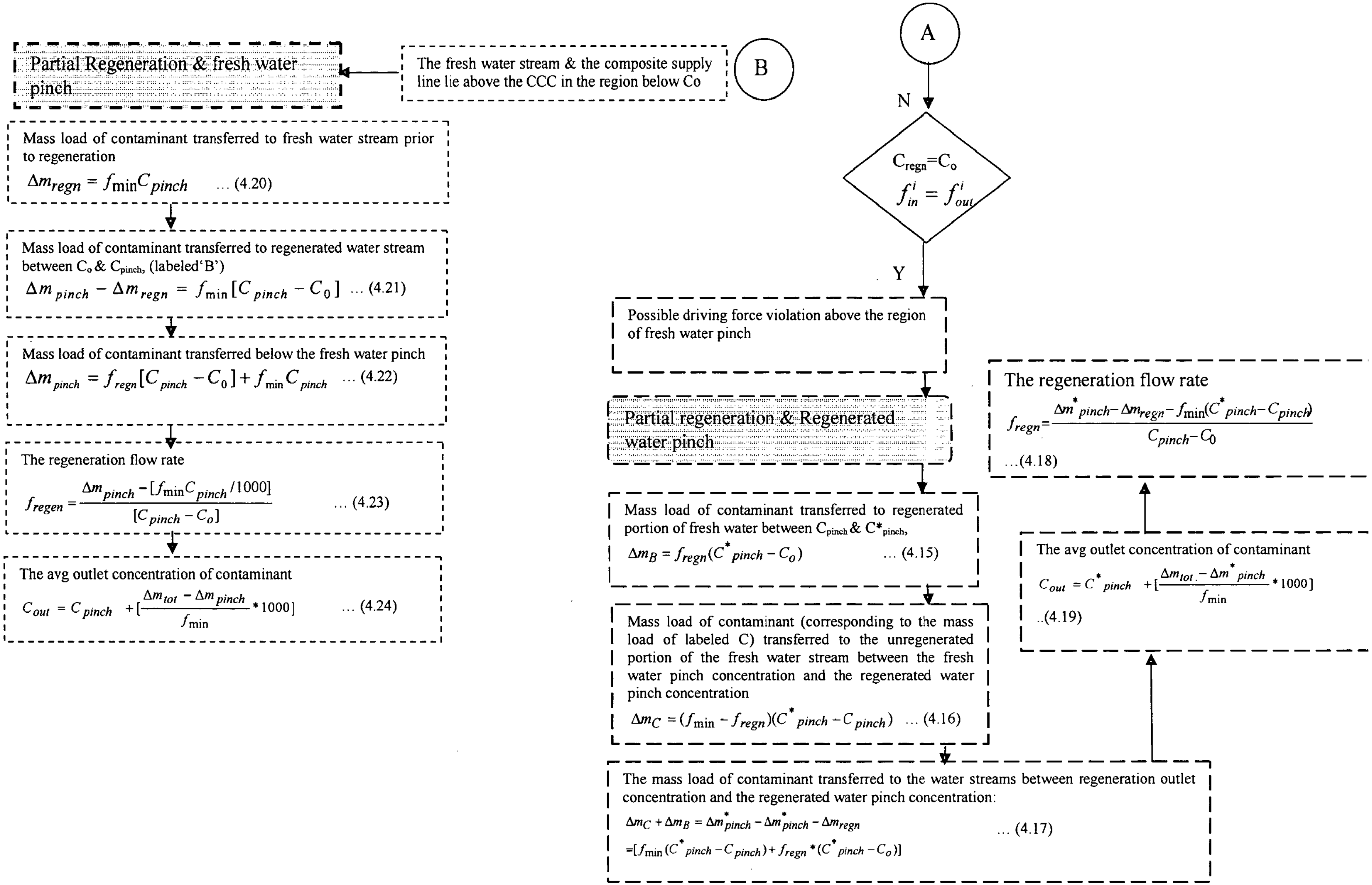


Fig. 14 (b) Algorithm for different regeneration approaches (Partial regeneration and fresh water pinch and partial regeneration and regenerated water pinch

Data Extraction –

- Extract Stream data from water using operations

If C_{regen}

Y → Simple Regeneration Recycle

The mass load of contaminant (corresponding to the mass load of contaminant labeled A) transferred prior to the regeneration is

$$\Delta m_{regen} = \frac{f_{\min} C_{pinch}}{1000} \quad \ldots (4.30)$$

Flow rate of waste water to be regenerated and recycled that causes the water supply line to just reach the fresh water pinch by the mass load of contaminant (corresponding to the mass load of contaminant labeled in B).

$$f_{regen} = \frac{\Delta m_{pinch} - \Delta m_{regen}}{C_{pinch} - C_o} = \frac{\Delta m_{pinch} - [f_{\min} C_{pinch}/1000]}{[C_{pinch} - C_o]} * 1000 \quad \ldots (4.31)$$

Flow rate of water recycled

$$f_{recycle} = f_{\min} + f_{regen} \quad \ldots (4.32)$$

The avg outlet concentration of contaminant

$$C_{out} = C^{*}_{pinch} + \frac{[\Delta m_{tot} - \Delta m^{*}_{pinch}]}{f_{\min}} * 1000 \quad \ldots (4.33)$$

N → Regeneration Recycle at regenerated water Pinch

Mass load of contaminant (labeled 'B') transferred to the regenerated water stream between the C_o & C_{pinch}

$$m_B = f_{regen}(C_{pinch} - C_o) \quad \ldots (4.26)$$

Mass load of contaminant (labeled 'C') transferred to the regenerated water stream that is not regenerated once again

$$m_C = f_{\min}(C^{*}_{pinch} - C_{pinch}) \quad \ldots (4.27)$$

Mass load of contaminant transferred below regenerated water pinch (corresponding to mass load of contaminant in labeled 'B'& labeled 'C')

$$m_B + m_C = f_{regen}(C_{pinch} - C_o) + f_{\min}(C^{*}_{pinch} - C_{pinch}) \quad \ldots (4.28)$$

The regeneration flow rate

$$f_{regen} = \frac{\Delta m^{*}_{pinch} - [f_{\min} C^{*}_{pinch}/1000]}{[C_{pinch} - C_o]} \quad \ldots (4.29)$$

Fig. 15 Algorithm for regeneration-recycling approach

4.3 Approach of Maan and Liu (Using concept developed by Wang and Smith)

When dealing with the multiple-contaminant problems, the design methodology for single contaminant cannot be used anymore. In multiple contaminant system, the key contaminant of each unit is different which is related to the water source to the unit. So the inlet and outlet flow rate allocation of each unit is difficult to specify because its freshwater consumption is close related to the choice of its sources. Due to the complexity, the design for water networks with single contaminants based on internal mains cannot be extended to that of multiple-contaminant systems.

The road map is first to identify the limitations of the single contaminant approach to multiple contaminant systems. Using concentration interval diagram (CID), concentration composite curve and water supply line to find the minimum fresh water flow rate in a multiple contaminant system. The next step is to investigate whether feasibility of reusing water leaving one water using operation within another operation with respect to secondary contaminant is possible or not. This procedure involves shifting the inlet and /or outlet concentration. The necessary design equations and methodology has been adapted from Mann & Liu (1999). In solving waste water minimization involving multi contaminants system, there are two well known schools of thoughts, i.e. the conceptual approach based on graphical analysis and mathematical programming approach based on MINLP. Both approaches discussed in following sections briefly:

4.3.1 Graphical technique

The graphical approach involves tools of concentration interval diagram, concentration composite curve and water supply lines to find the minimum fresh water flow rate in a multiple contaminant systems. The stepwise procedure is explained below:

Step 1 → Data Extraction →

A set of i water-using processes involving a set of J contaminants. The problem formulation starts by defining for each process the limiting water flow rate f_i, the inlet concentration limits C_{in} and outlet concentration limits C_{out}

$$C_{i,in} = \{C_{i1,IN}, C_{i2,IN}, C_{i3,IN} \ldots\ldots C_{iJ,IN}\} \quad ..(4.4)$$

$$C_{i,out} = \{C_{i1,out}, C_{i2,out}, C_{i3,out} \ldots\ldots C_{iJ,out}\} \quad ..(4.5)$$

Where $C_{ij,IN}$ and $C_{ij,out}$ are the inlet and outlet concentration limits of process i with respect to contaminant J.

Step 2 → Limiting water profiles →

The limiting water profiles useful to determine the concentration level at which contaminant B limits water reuse. The limiting water profile is a plot of concentrations of contaminant A at the inlet and outlet of each operation versus the total mass of A transferred. **Fig 4.16** shows the general representation of limiting water profiles. **Fig 4.16** shows the concentrations of contaminants A & B at each CIB (concentration interval boundary) in brackets for each operation. For two contaminants A, B, the water supply line gives the proportional mass transfer relationship:

$$\frac{C_{iA,n} - C_{iB,n}}{C_{iA,out} - C_{iB,in}} = \frac{C_{iB,n} - C_{iB,n}}{C_{iB,out} - C_{iB,in}} \quad ..(4.34)$$

Step 3 | Method of *concentration shift*

Inlet Concentration shift & water reuse and feasibility

In order to maintain the feasibility of reuse of water from one operation to another operation, sometimes it is necessary to perform *inlet concentration shift* of contaminant as shown in **Fig. 4.17**. As shown in it, consider two operations *i* and *j*, involving two contaminants A and B.

Fig.4.17 (a) represents the limiting water profiles for contaminant A prior to an internal concentration shift and **Fig. 4.17(b)** represents the same following an inlet concentration shift on operation *j*.

Outlet Concentration shift & water reuse feasibility

The next step is to investigate the feasibility of reusing the water from the outlet of operation *i* within operation *j*. **Fig.4.18 (a)** represents the limiting water profiles for contaminant A prior to an internal concentration shift.

Fig. 4.18(b) shows the limiting water profiles for operation *i* and *j* to aid in determination of the reference concentration of the contaminant at the outlet of operation *j*, $C^*_{j,out}$ assuming A to be limiting. Eq.4.8 is used to determine the reference concentration.

$$\frac{C^*_{j,n} - C^*_{j,in}}{C^*_{j,out} - C^*_{j,in}} = \frac{C_{j,A,n} - C_{j,A,in}}{C_{j,A,out} - C_{j,A,in}} \quad ..(4.35)$$

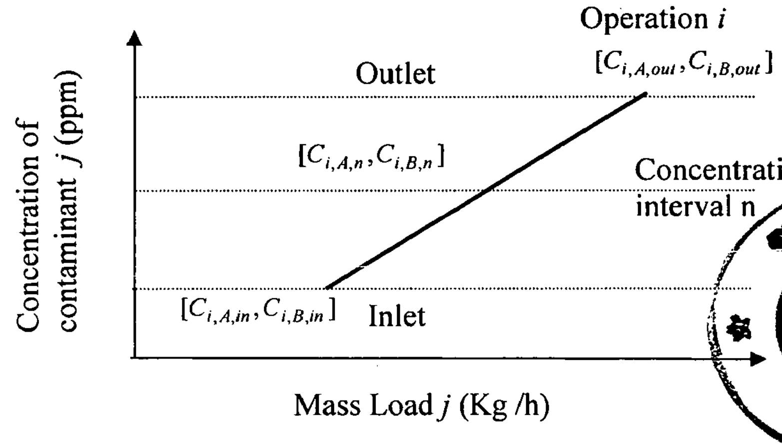
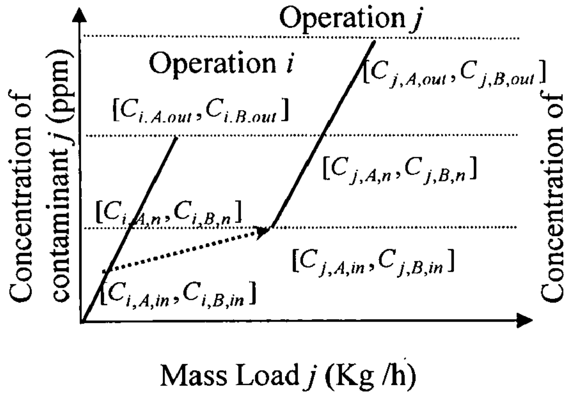
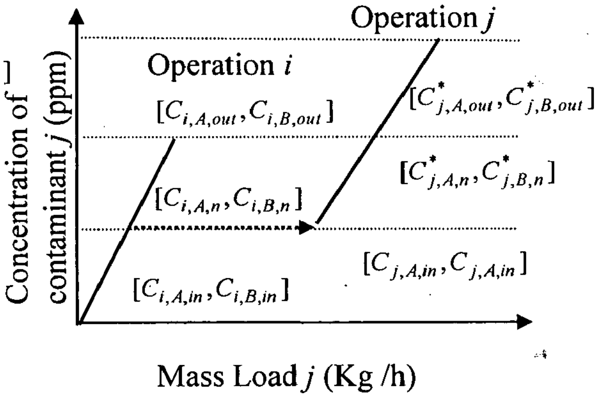


Fig. 4.16 A general representation of the notations for the proportional mass transfer assumption in a multiple contaminant system



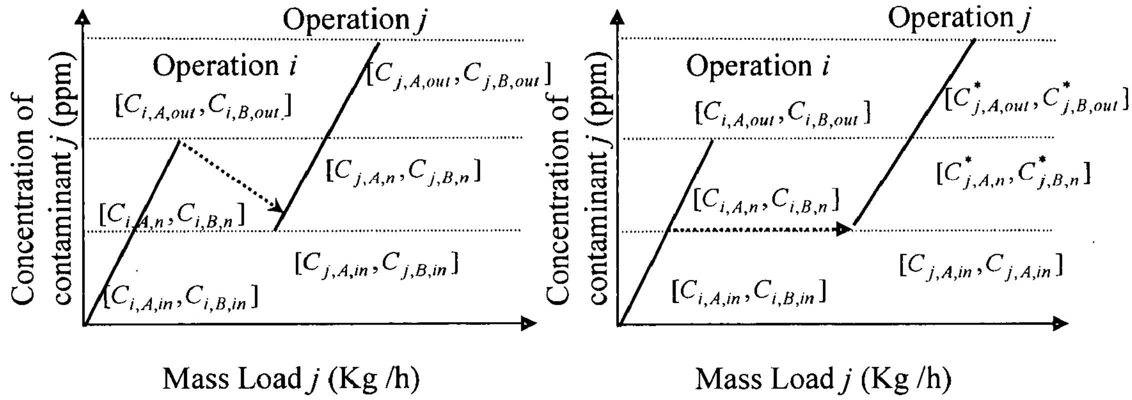


.... Reuse from operation i to j

* indicates new concentration after inlet concentration shift

Fig. 4.17 (a) Limiting water profiles for contaminant A before *inlet concentration shift*

Fig. 4.17 (b) Limiting water profiles for contaminant A after *inlet concentration shift*



.... Reuse from operation *i* to *j*

* indicates new concentration after outlet concentration shift

Fig. 4.18 (a) Limiting water profiles for contaminant A before *outlet concentration shift*

Fig. 4.18 (b) Limiting water profiles for contaminant A after *outlet concentration shift*

4.3.2 Design Equations for finding the minimum freshwater flow rate.

This section first develops the design equations for finding the minimum fresh water flow rate. As shown in **Fig.4.19**, consider the general concentration –interval boundary. There are three types of operations existing at this interval. In **Fig.4.20**, $T_{i,n}$ and $T_{i,n+1}$ represent the flow rate of water available for reuse within the operation *i* at the concentration interval boundaries *n* & *n+1* respectively. $W_{ij,n}$ and $W_{ij,n+1}$ denote the concentrations (ppm) of contaminant j in operation i in water streams available for water reuse within operation *i* with flow rate $T_{i,n}$ and $T_{i,n+1}$ respectively. $F_{i,n}$ is the flow rate of fresh water supplied to operation *i* at concentration interval boundary *n*. $q_{li,m\le n}$ is the flow rate of water from operation *i* at the concentration-interval boundary *n* that is supplied by (or reused from) operation *l* at a concentration interval boundary *m* smaller than *n* and $W_{lj,m\le n}$ is the corresponding concentration of the contaminant *j* in the water stream with flow rate $q_{li,m\le n}$.

Stepwise procedure to calculate the fresh water requirement of each operation at each concentration-interval boundary as follows (Wang and Smith (1994)):

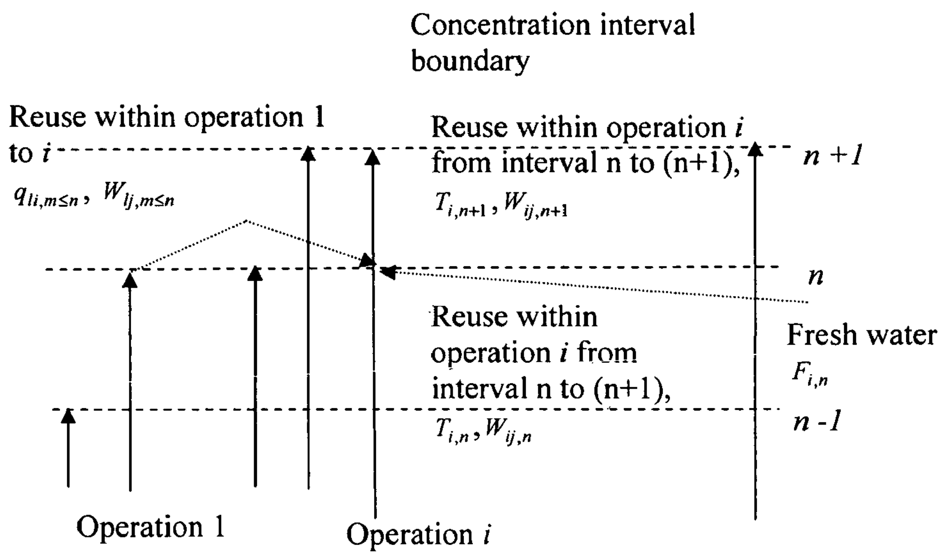


Fig. 4.19 General concentration interval boundary below the pinch interval boundary

4.3.3 Pinch Interval Water reuse

In some cases, the design equations for multiple contaminant targeting will not be appropriate for concentration interval boundary below the pinch. This is because of the possibility of reusing water that has reached the pinch interval boundary at the preceding interval boundaries. In such cases, it is necessary to consider the possibilities of reusing water that has reached the pinch interval boundary in other operations in previous intervals (Wang & Smith, 1994). The problem is solved by using Eq.36 to 45 as given below:

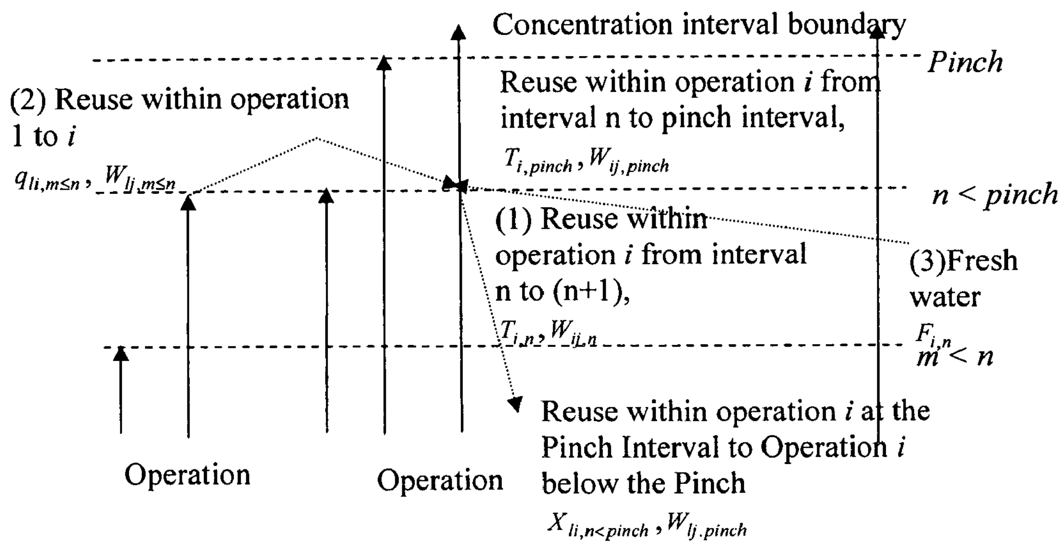


Fig. 4.20 General concentration interval boundary below the pinch interval boundary with pinch internal reuse

Step 1

Define the fraction $\phi_{i,n}$ as the ratio of the actual flow rate to operation i at concentration interval boundary n, $f^*_{i,n}$ to the limiting flow rate to operation i as

$$\phi_{i,n} = \frac{f^*_{i,n}}{f_i} \quad ..(4.36)$$

The required flow rate for operation i is then

$$f^*_{i,n} = \phi_{i,n} f_i \quad ..(4.37)$$

Step 2

The fresh water requirement, outlet concentrations and outlet flow rates of each operations that begins at the first concentration-interval boundary ($n = 1$) using Eq.4.9 and Eq. 4.10. It is possible to identify which contaminant requires the greatest fraction of the limiting flow rate for each operation through Eq.4.11.

$$\phi_{i,1} = \max_j \left[\frac{C_{ij,2} - C_{ij,1}}{C_{ij,2}}\right] \quad ..(4.38)$$

Step 3

After identifying the limiting contaminant in each operation, calculate the freshwater requirement for each operation through Eq.4.10 or 4.12, which also provides the flow rate of water available for water reuse in the same operation at the second concentration interval boundary:

$$\phi_{i,1} f_i = F_{i,1} = T_{i,2} \quad ..(4.39)$$

The change in concentration in the water passing through each operation is obtained through Eq. 4.13

$$W_{ij,2} = W_{ij,1} + \frac{f_i (C_{ij,2} - C_{ij,1})}{T_{i,2}} \quad ..(4.40)$$

Step 4

Evaluate the fresh water requirement, outlet concentrations, and outlet flow rates of each operation at the next concentration-interval boundary. Any operation that ends at this concentration interval boundary is eligible for reuse in other operations existing at this concentration interval boundary. Eq. 4.14 to 4.16 solve simultaneously for the freshwater requirement.

$$f_{i*,n} = T,n_i + q_{l,i} + F_{i,n} = \phi_{i,n} f_i \quad ..(4.41)$$

$$\phi_{i,n} = \max_j [\frac{C_{ij,n+1} - C_{ij,n}}{C_{ij,n+1} - W_{avgij,n}}] \quad ..(4.42)$$

$$W_{avgij,n<pinch} = \frac{T_{i,n} W_{ij,n} + \sum_l q_{li,m<n} W_{ij,m<n}}{T_{i,n} + \sum_l q_{li,m<n} + F_{i,n}} \quad ..(4.43)$$

Calculate the flow rate and concentrations of water available for reuse in the next concentration interval from

$$T_{i,n+1} = F,n_i + T_{i,n} + \sum_i q_{li,m<n} \quad ..(4.44)$$

$$W_{ij,n+1} = W_{avgij,n} + [\frac{f_i * (C_{ij,n+1} - C_{ij,n})}{T_{i,n+1}}] \quad ..(4.45)$$

Step 1

Fig. 4.20 illustrates the general concentration –interval boundary immediately below the pinch. When considering concentration interval boundaries below the pinch (*n* < *pinch*), the total flow rate to an operation *i* at this interval by Eq. 4.46

$$f^*_{i,n<pinch} = fT_{i,n<pinch} + q_{li,m<n} + F_{i,npinch} + X_{li,n<pinch} = \phi_{i,n<pinch} f_i \quad ..(4.46)$$

Step 2

Where the new water sources $X_{li,n<pinch}$ h is the flow rate returned from operation 1 at the pinch interval boundary to operation *i* at the n^{th} concentration interval boundary (*n*<*pinch*).The flow rate weighted concentration of contaminant *j* in operation *i* at the n^{th} concentration interval boundary, based on four water sources by Eq.4.20

Calculate the flow rate and concentrations of water available for reuse in the next concentration interval from

$$W_{avgij,n<pinch} = \frac{T_{i,n<pinch}W_{ij,n<pinch} + \sum_{1} q_{li,m<n}W_{ij,m<n} + \sum_{1} X_{li,n<pinch}W_{ij,pinch}}{T_{i,n<pinch} + \sum_{1} q_{li,m<n} + \sum_{1} X_{li,pinch} + F_{i,n<pinch}} \quad ..(4.47)$$

Step 3

The Eq. 4.37, 4.39 and 4.43 reduces to following Eq. 4.48, 4.49, 4.50 when no fresh water is allowed:

$$f_{i*,pinch} = T_{i,pinch} + q_{li,m<pinch} = \phi_{i,pinch} f_i \quad ..(4.48)$$

$$\phi_{i,pinch} = \max_{j}\left[\frac{C_{ij,pinch+1} - C_{ij,pinch}}{C_{ij,pinch+1} - W_{avgij,pinch}}\right] \quad ..(4.49)$$

$$W_{avgij,pinch} = \left[\frac{T_{i,pinch}W_{ij,pinch} + \sum_{1} q_{li,m<pinch}W_{li,m<pinch}}{T_{i,pinch} + \sum_{l} q_{li,m<pinch}}\right] \quad ..(4.50)$$

Step 4

Evaluate the possibility of reusing each water stream available at the pinch interval into each operation that exists at the previous concentration intervals.

$$\phi_{i,n<pinch} = [\frac{C_{ix,pinch} - C_{ix,n<pinch}}{C_{ix,pinch} - W_{avgix,n<pinch}}] = \frac{C_{ij,pinch} - C_{ij,n<pinch}}{C_{ij,pinch} - W_{avgij,n<pinch}} \quad ..(4.51)$$

$$T_{i,n<pinch} + q_{li,m<pinch} + F_{i,n<pinch} + X_{li,n<pinch} = \phi_{i,n<pinch} f_i \quad ..(4.52)$$

$$W_{avgij,n<pinch} = \frac{T_{i,n<pinch} W_{ij,n<pinch} + \sum_{1} q_{li,m\le n} W_{ij,m\le n} + \sum_{1} X_{li,n<pinch} W_{ij,pinch}}{T_{i,n<pinch} + \sum_{1} q_{li,m\le n} + \sum_{1} X_{li,pinch} + F_{i,n<pinch}} \quad .. (4.53)$$

Step5

The highest ranking reuse option is made and the concentrations at the pinch interval are updated for operation *i*.

Step6

Reevaluate the potential fresh water savings for each stream involved in the reuse options made in step 5 and repeat until no other reuse options

4.4. Approach of Kim and Smith (2001)

Designing steps for cooling water networks

The current practice for cooling water network design most often follows parallel network configurations, where cooling water with the same temperature is supplied to all coolers. However, coolers do not always require cooling water at the same cooling water supply temperature when inlet cooling water temperature conditions are not too sensitive to the thermal performance of coolers. Appropriate manipulations of cooling water conditions to the coolers might allow the cooling water network to be changed from a parallel to a series design and/or combined series-parallel design. Cooling water configurations with cooling water reuse will return cooling water with a higher temperature and lower flow rate, where the cooling tower removes more heat from the water and allows a higher heat load for the tower. Based on this idea, retrofit design methods for cooling systems had been developed by Kim & Smith as shown below:

Step 1: Define a limiting cooling water profile

"A limiting cooling water profile" is defined as the inlet and outlet temperatures for a cooling water stream that features the maximum allowable temperatures. These are chosen to comply with the thermal performances of an existing cooler in retrofit cases. These limiting conditions are limited by the "minimum temperature difference" (ΔT_{min}) or other process constraints. **Fig. 4.21** represents the temperature-enthalpy curve (limiting cooling water profile) for each individual stream.

Step 2: Construct a cooling water composite curve (CWCC)

A "cooling water composite curve" is constructed by combining individual limiting profiles as shown in **Fig. 4.22**. This single composite curve is created by adding all enthalpy changes within the same temperature interval and representing it as a single line. The design of the cooling water network will be based on the cooling water composite curve, which represents overall limiting conditions of the whole network.

Step 3: Identification of feasible design region for cooling water supply

The cooling water supply line can be drawn against the composite curve. An increase in slope of a supply line indicates a decrease in a flow rate and increase in temperature for cooling water return to the tower. A lower bound of flow rate corresponds with a parallel network design of coolers, while an upper bound of flow rate is limited by the composite curve creating a pinch. As shown in **Fig.4.22**, the cooling water supply line is a straight line matched against the cooling water composite curve to represent the overall cooling water flow rate and maximum rise in temperature achieved by the said flow rate. Maximizing the outlet temperature of the cooling water supply line minimizes the flow rate of cooling water by maximizing cooling water re-use.

The procedure of cooling water networks is divided into two parts: targeting and design.

Step 4: Targeting cooling water supply conditions to cooling tower

As different cooling water streams can have different exit (return) temperatures, it will affect the performance of the cooling tower, where the desired heat removal from the cooling water is achieved. The maximum input temperature and cooling water flow rate to cooling tower is fixed by the cooling water supply line for maximum reuse (upper bound).

Step 5: Design of cooling water network

The implementation of limiting water flow rate and maximum discharge temperature from cooling water network, determined in step 4, requires that a new configuration of coolers be designed to achieve the target conditions.

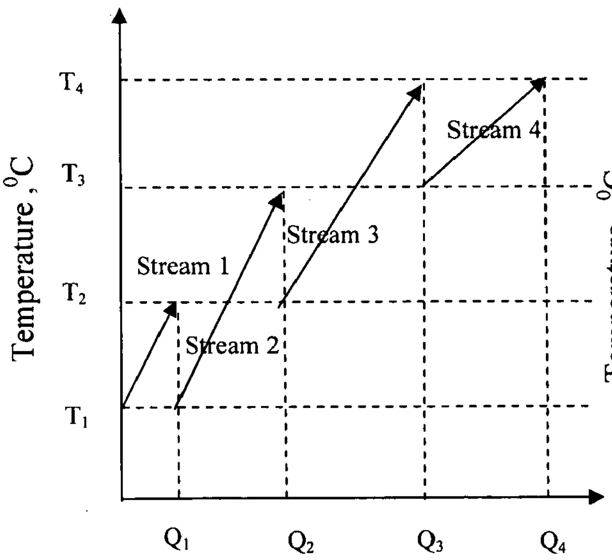


Fig.4.21 Temperature Enthalpy diagram of different streams involved in a network

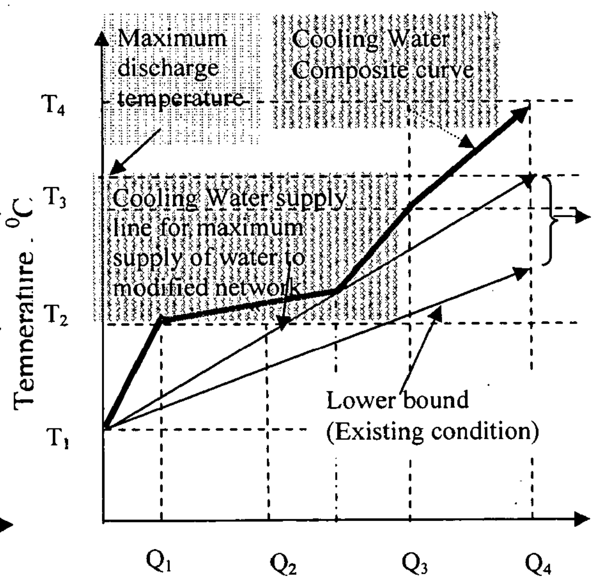


Fig.4.22 Cooling water composite curve targeting for maximum reuse

CHAPTER 5

RESULTS AND DISCUSSIONS

This Chapter discusses the results obtained by solving different water system design problems (as defined in chapter 3 as problem 3.1 to 3.5). The stream input data for these problems are given in Table 3.1, Table 3.2, Table 3.3 (a) & 3.3 (b), Table 3.4 and Table 3.5. The description, of these problems, is provided in Appendix-A (A.1 to A.5). These water system design problems are analyzed and optimum designs of water using networks were developed by different solution techniques as explained in detail in Chapter 4.

5.1 SALIENT RESULTS OF PROBLEM 3.1

In the present case study the saving of DM water and decrease of waste water can be done through several means, which includes *reuse, regeneration–reuse and regeneration- recycling.*

5.1.1 Water *Reuse* technique

The first step in the present investigations is to save DM water by allowing reuse of it. Using the computer program developed in MATLAB, the CID has been generated and tabulated in **Table 5.1**. Accordingly the CCC for the problem has been plotted and shown in **Fig. 5.1**.

Table 4 which is prepared to find out the extent of reuse shows that minimum fresh water requirement is 31.9 tph when reuse is allowed in the network and freshwater pinch concentration is 30 ppm. It can be seen that before the application of water pinch the DM water consumption was 50 tph. **Fig.5.1** shows how the minimum fresh water flow (31.9 tph) rate is arrived at using the CCC. **Fig. 5.2** shows the block diagram of the modified network which can facilitate water reuse.

Table 5.1 CID for water *reuse technique*

Concen. (ppm)	1	2	3	4	Mass Load (kg/h)	Cumul. Mass Load (kg/h)	Flow rate (tph)
1						0	0
					0.05		
5						0.05	9.6
					0.13		
10						0.18	1.78
					0.4		
20						0.58	28.9
					0.38		
30						0.96	31.93
					0.24		
40						1.2	29.95
					2.6		
300						3.8	12.66

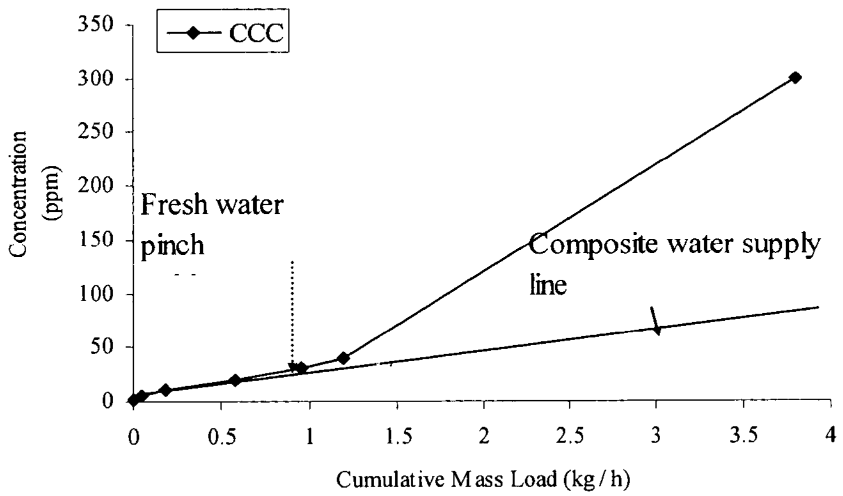


Fig.5.1 CCC and Composite water supply line (*reuse* technique)

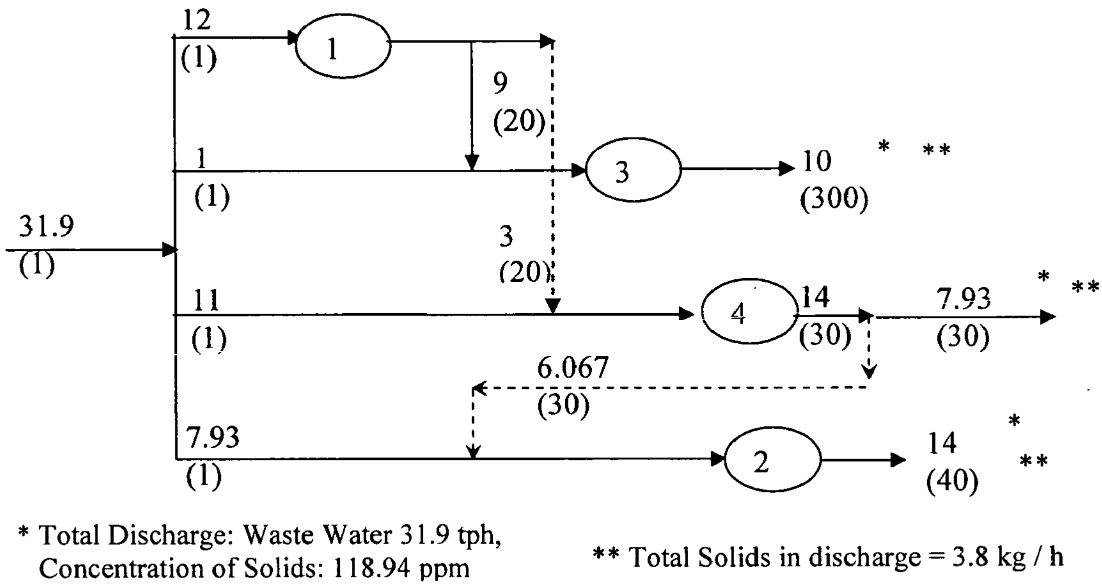


Fig. 5.2 Modified water network (*reuse* technique)

5.1.2 Water *regeneration-reuse* technique

The second step in the further reduction of DM water and waste water is to go for *full* regeneration *& regenerated water pinch.* For this purpose **Table 5.2** is generated. It shows that the DM water flow rate can be further decreased to 307.2 tph. In this case also the fresh water pinch remains at 30 ppm. **Fig.5.3** shows how the fresh water consumption in the case of *full regeneration & regenerated water pinch* .is arrived at. **Fig. 5.4** shows the block diagram of the modified network which can facilitate *full regeneration & regenerated water pinch* to decrease the fresh water consumption

Note: *Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.*

Table 5.2 CID for *regeneration technique*

Concen. (ppm)	1	2	3	4	Mass Load (kg/h)	Cumul. Mass Load (kg/h)	Flow rate (tph)
1						0	0
					0.05		
5						0.05	9.6
					0.13		
10						0.18	17.80
					0.4		
20						0.58	28.90
					0.38		
30						0.96	31.93
					0.24		
40						1.2	29.95
					2.6		
300						3.8	12.66

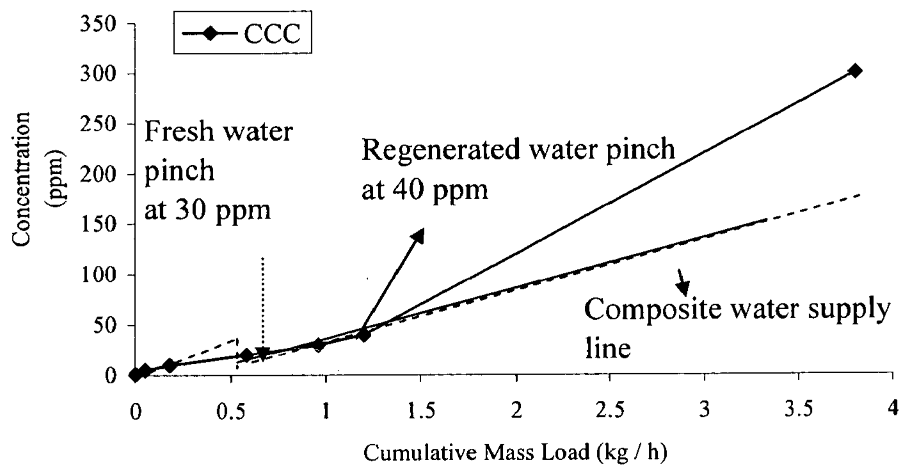


Fig. 5.3 CCC and composite water supply line (*regeneration -reuse* technique)

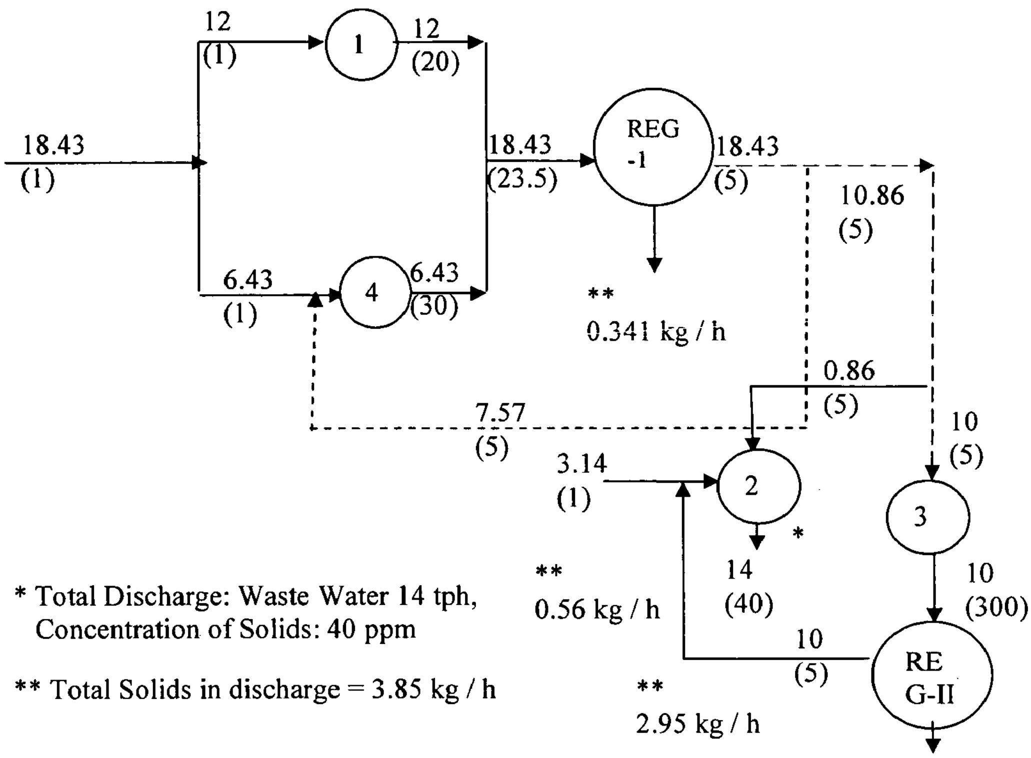


Fig. 5.4 Modified Water Network (*regeneration -reuse* technique)

5.1.3 Water *regeneration-recycling* technique

In the third step the fresh water content is further decreased by using the concept of *regeneration-recycle*. For this purpose **Table 5.3** is generated. It clearly shows that the fresh water consumption has further been decreased to 120 tph. The methodology of determination of fresh water consumption using the concept of *regeneration-recycle* is shown in **Fig. 5.5**. The modified network which based on the above concept is given in **Fig. 5.6.**

Note: *Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.*

Table 5.3 CID for *regeneration-recycling technique*

(Regeneration recycling at regenerated water pinch is provided.)

Concen. (ppm)	1	2	3	4	Mass Load (kg/h)	Cumul. Mass Load (kg/h)	Flow rate (tph)	Full regeneration flow rate(tph)
1						0	0	
					0.05			
5						0.05	9.6	
					0.02			
5.9						0.07	12.1	
					0.11			
10						0.18	17.80	
					0.4			
20						0.58	28.90	
					0.38			
30						0.96	31.93	24.69
					0.24			
40						1.2	29.95	29.62
					2.6			
300						3.8	12.66	6.95

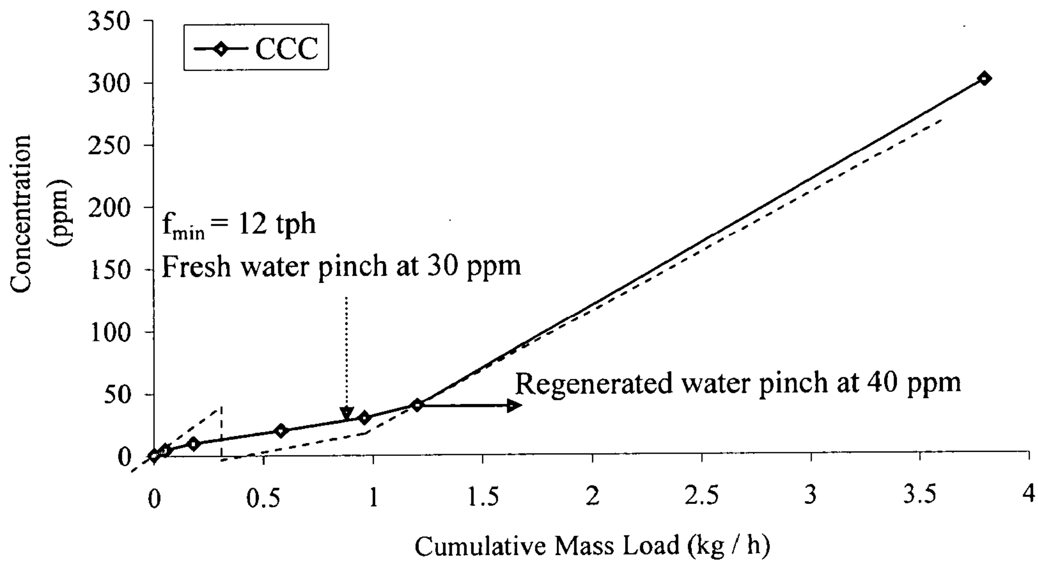
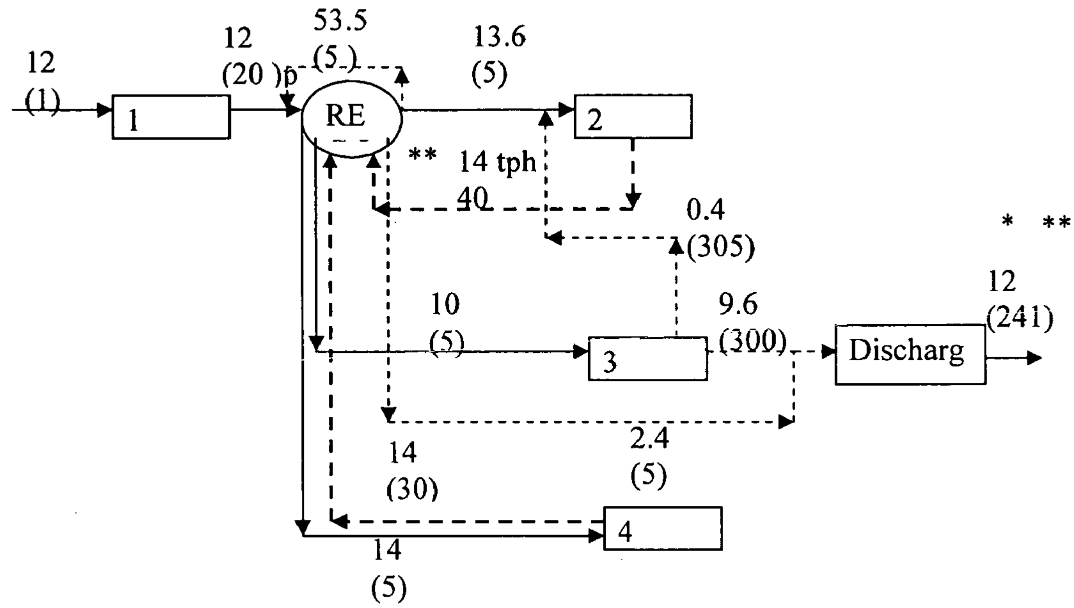


Fig. 5.5 CCC for Modified Water Network (*regeneration –recycling* technique)



* Total Discharge: Waste Water 12 tph, Concentration of Solids: 241 ppm

** Total Solids in discharge = 3.8 kg / h

Fig. 5.6 Modified Water Network (*regeneration –recycling* technique)

Note: *Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.*

The detail calculation of cost benefit analysis has been explained in section 6.2 of chapter 6.

5.2 SALIENT RESULTS OF PROBLEM 3.2

The first step in the present investigations is to save DM water by allowing reuse of these in their respective networks. Using Algorithm and program developed in MATLAB, the CID of DM water using operations has been generated and tabulated in **Table 5.4. Table 5.4** which was prepared to find out the extent of reuse of DM water shows that minimum DM water requirement is 59.8 tph when reuse is allowed in the network and DM water pinch concentration is 60 ppm. It can be seen that before the application of water pinch the DM water consumption was 69 tph. **Fig. 5.7** shows how the minimum DM water flow (59.3 tph) rate is arrived at using the CCC. **Fig. 5.8** shows the block diagram of the modified network which can facilitate DM water reuse to decrease the DM water consumption.

The second step in the further reduction of DM water and waste water is to go for *full regeneration & regenerated water pinch.* Using Algorithm shown and program developed in MATLAB, the CID of DM water using operations has been generated and tabulated in **Table 5.5.** It shows that the DM water flow rate can be further decreased to 34.5 tph. In this case also the DM water pinch remains at 60 ppm and regenerated water pinch occurs at 200 ppm. Fig. shows how the DM water consumption in the case of full *regeneration & regenerated water pinch* is arrived at. **Fig. 5.9** shows the block diagram of the modified network which can facilitate *full regeneration & regenerated water pinch* to decrease the DM water consumption

Table 5.4 CID of DM water using operations, representing limiting water flow rate & water pinch point

Concen. (ppm)	**PS-I**	**PS-II**	**R**	**DW**	**S-4**	**Mass Load (kg/h)**	**Cumulative Mass Load (kg/h)**	**Flow rate (tph)**
1	↑						0	0
	│					0.12		
5	│	↑					0.12	24
	│	│				0.2		
10	│	│	↑				0.32	32
	│	│	│			0.26		
15	│	│	│	↑			0.58	38.67
	│	│	│	│		0.64		
25	│	│	│	│	↑		1.22	48.80
	│	│	│	│	│	1.73		
50	│	│	│	│	│		2.95	59.00
	│	│	│	│		0.64		
60	│	│	│	│			3.59	59.83
		│	│	│		4.76		
200		│	│	│			8.35	41.75
			│	│		3.60		
350			│	│			11.95	34.14
			│			1.56		
480			│				13.51	28.15

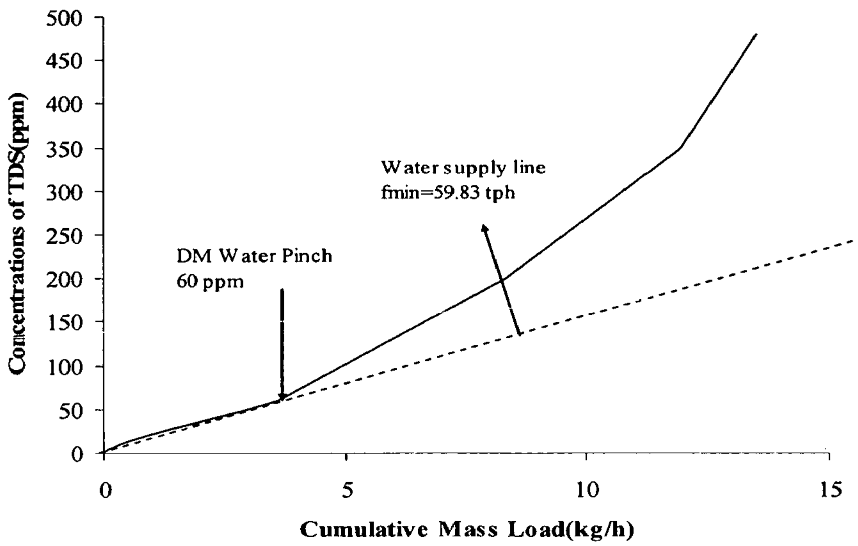


Fig. 5.7 CCC for Modified Water Network (*reuse* technique)

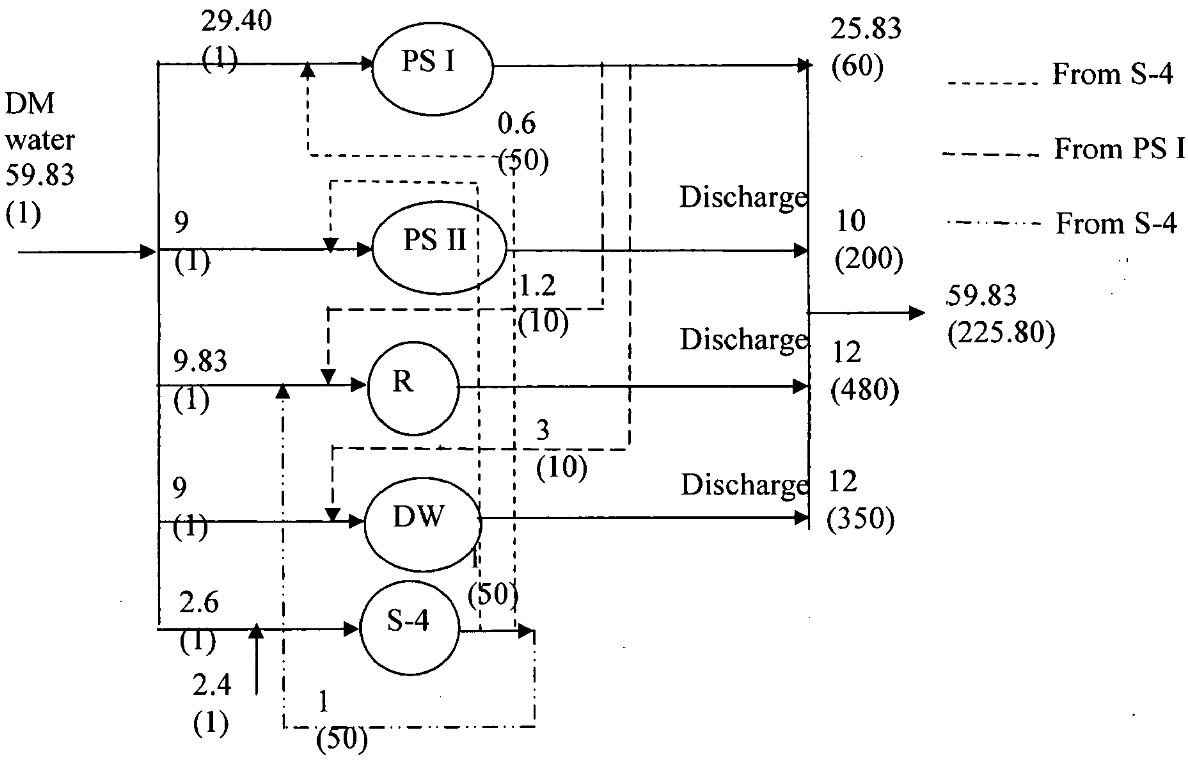


Fig. 5.8 Modified Water Network (*reuse* technique)

Note: *Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.*

Table 5.5 CID of DM water network representing limiting water flow rate & water pinch point (full regeneration at regenerated water pinch (Co=5 ppm)

Concen. (ppm)	PS-I	PS-II	R	DW	S-4	Mass Load (kg/h)	Cumulative Mass Load (kg/h)	Flow rate (tph)	Full Regeneration flow rate (tph)
1	↑						0	0	
	│					0.12			
5	│	↑					0.12	24	
	│	│				0.2			
10	│	│	↑				0.32	32	
	│	│	│			0.26			
15	│	│	│	↑			0.58	38.67	
	│	│	│	│		0.64			
25	│	│	│	│	↑		1.22	48.80	
	│	│	│	│	│	1.73			
50	│	│	│	│	│		2.95	59.00	
	│	│	│	│		0.64			
60	│	│	│	│			3.59	59.83	31.22
		│	│	│		4.76			
200		│	│	│			8.35	41.75	32.75
			│	│		3.60			
350			│	│			11.95	34.14	29.51
			│			1.56			
480			│				13.51	28.15	25.55

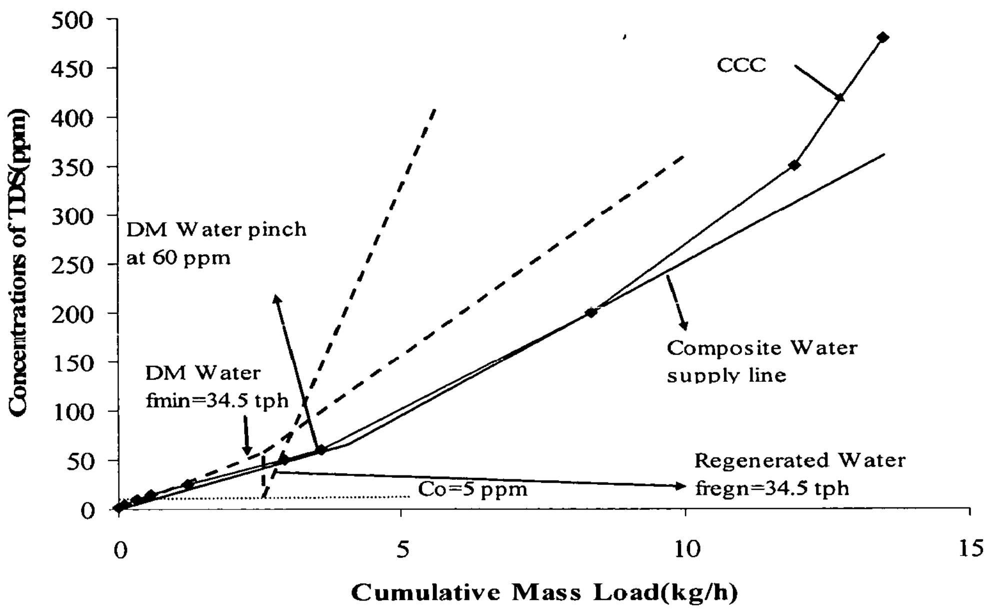


Fig. 5.9 CCC for Modified Water Network (*regeneration-reuse* technique)

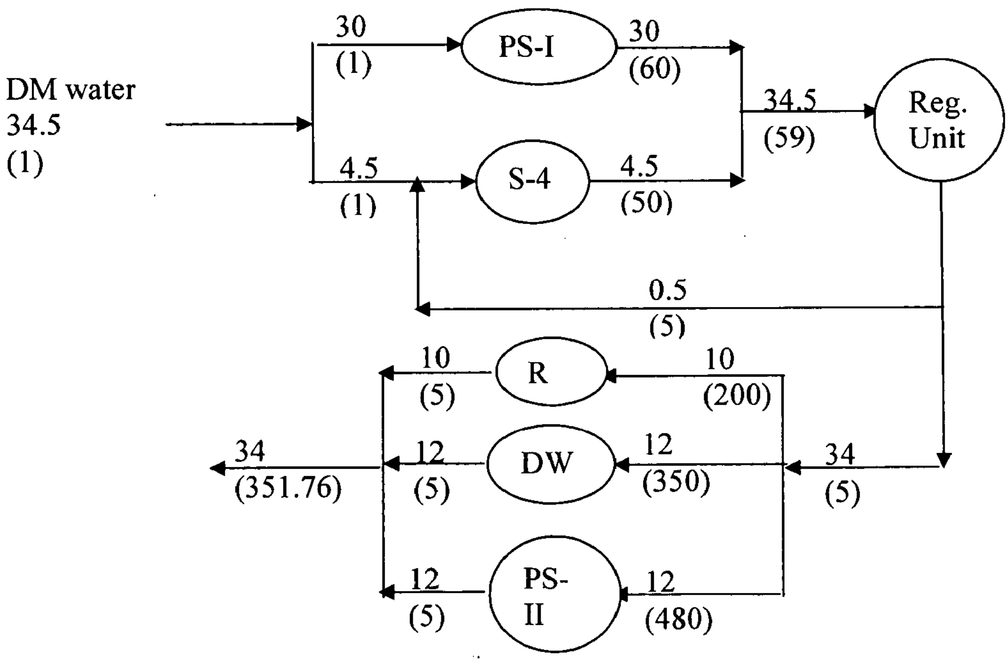


Fig. 5.10 Modified Water Network (*regeneration-reuse* technique)

Note: *Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.*

In the third step the DM water content is further reduced by using the concept of *regeneration-recycling.* Using Algorithm shown and program developed in

MATLAB, the CID of DM water using operations has been generated and tabulated in **Table 5.6**. It shows that the DM water flow rate can be further reduced to 24 tph. In this case also the DM water pinch remains at 60 ppm. **Fig. 5.10** shows how the DM water consumption in the case of *regeneration recycling & regenerated water pinch* .is arrived at. **Fig. 5.10** shows the block diagram of the modified network which can facilitate *regeneration-recycle & regenerated water pinch* to decrease the DM

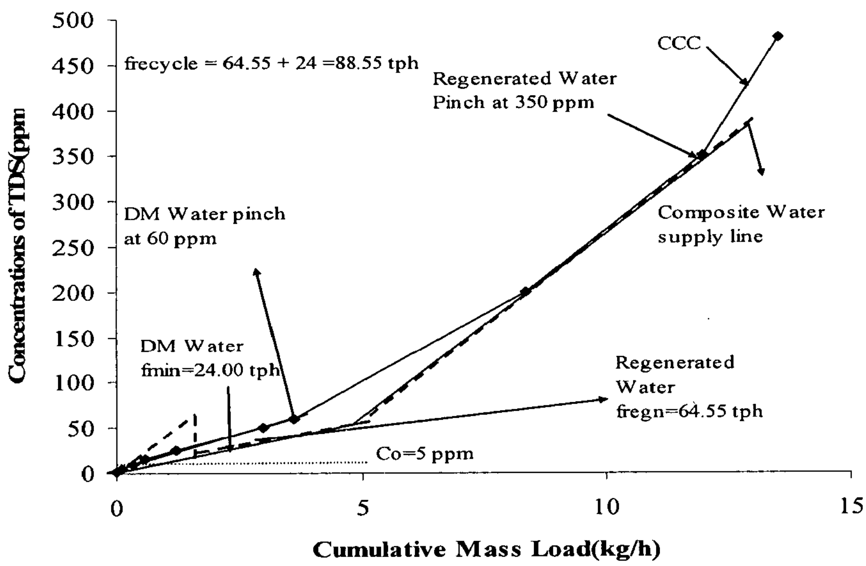


Fig. 5.11 CCC (*regeneration-recycling* technique)

The detail calculation of cost benefit analysis has been explained in **section 6.3 of chapter 6.**

Table 5.6 CID of DM water network, representing limiting water flow rate at regeneration recycle & regenerated water pinch, Co = 5 ppm

Concen. (ppm)	PS-I	PS-II	R	DW	S-4	Mass Load (kg/h)	Cumulative Mass Load (kg/h)	Flow rate (tph)	Regeneration Recycle flow rate (tph)
1							0	0	
						0.12			
5							0.12	24	
						0.2			
10							0.32	32	
						0.26			
15							0.58	38.67	
						0.64			
25							1.22	48.80	
						1.73			
50							2.95	59.00	
						0.64			
60							3.59	59.83	39.09
						4.76			
200							8.35	41.75	64.55
						3.60			
350							11.95	34.14	64.55
						1.56			
480							13.51	28.15	36.18

Note: *Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.*

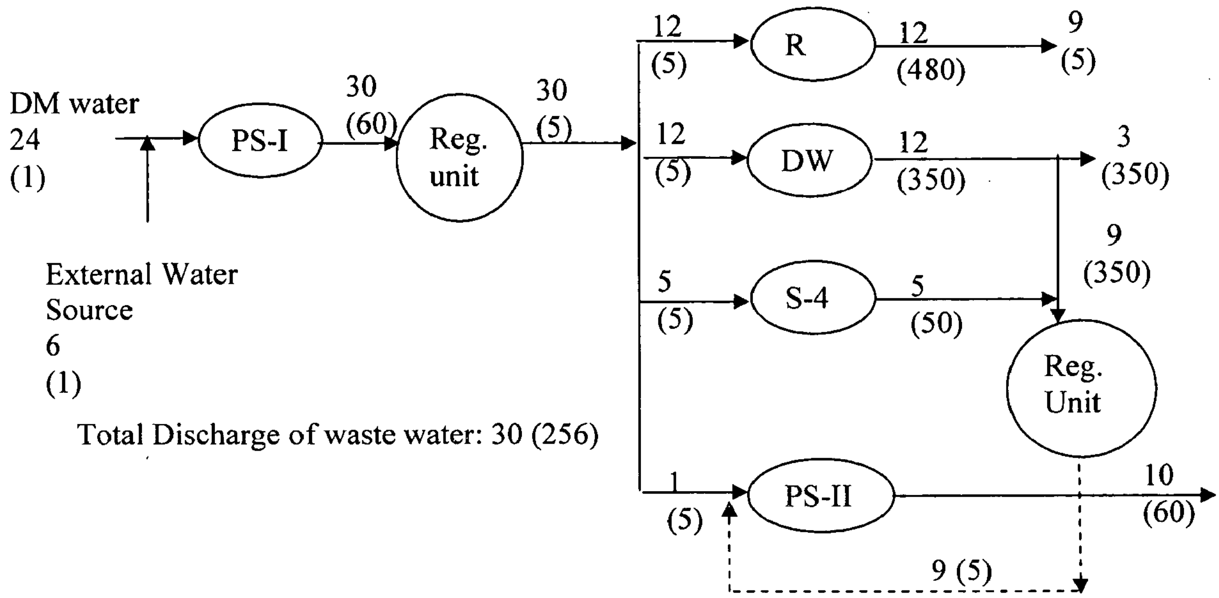


Fig. 5.12 Modified Water network (*regeneration-recycling* technique)

5.3 SALIENT RESULTS OF PROBLEM 3.3

The first step in the present investigations is to save DM water by allowing reuse of these in their respective networks. Using Algorithm and program developed in MATLAB, the CID of DM water using operations has been generated and tabulated in **Table 5.7**. **Fig. 5.13** shows how the minimum DM water flow rate is arrived at using the CCC. **Fig. 5.14** shows the block diagram of the modified network which can facilitate DM water reuse to decrease the DM water consumption.

Table 5.7 CID of DM water network, representing limiting water flow rate (*reuse* technique)

Concentration (ppm)	Mass Load (kg/h)	Cumulative Mass Load (kg/h)	Flow rate (tph)
0		0	0
	0.2		
20		0.2	10
	0.21		
25		0.41	16.22
	0.32		
30		0.73	24.19
	2.68		
55		3.40	61.90
	8.11		
85		11.51	135.43
	2.39		
95		13.90	146.35
	0.98		
100		14.88	148.84
	1.86		
110		16.75	152.23
	8.52		
175		25.26	144.34
	5.28		
205		30.54	148.98
	17.6		
320		48.14	150.44
	3.24		
350		51.38	146.8
	2		
400		53.38	133.45
	13.64		
620		67.02	108.10
	10.07		
810		77.09	95.17

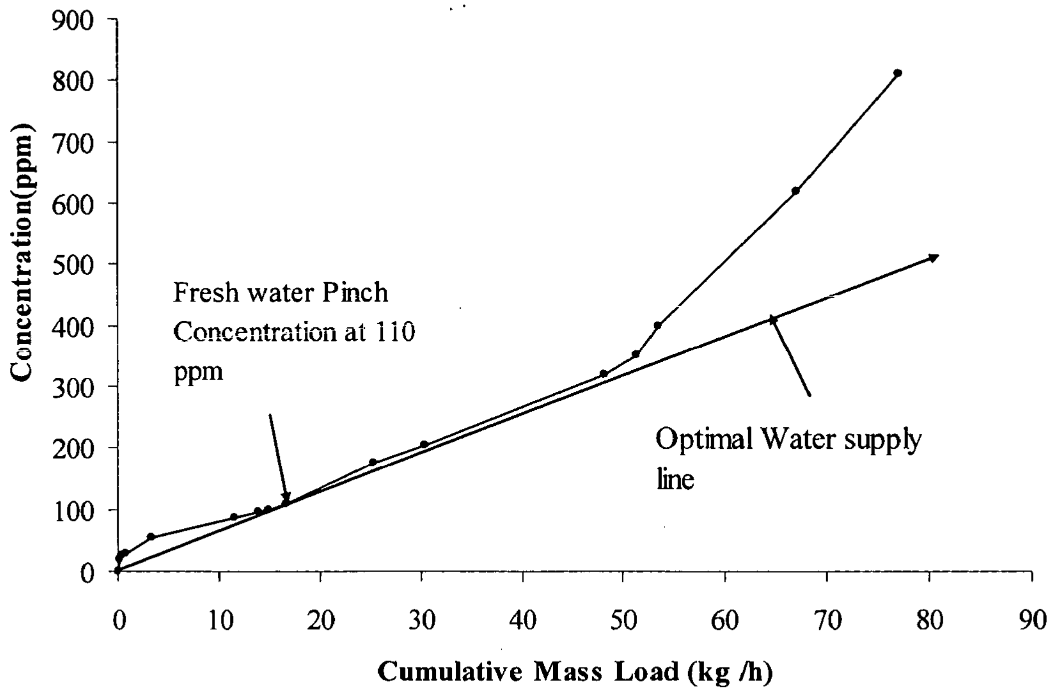


Fig. 5.13 CCC (*reuse* technique)

The detail calculation of cost benefit analysis has been explained in **section 6.4 of chapter 6.**

Note: *Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.*

- Total Discharge flow rate : 223tph
- Solids in discharge : 369 ppm

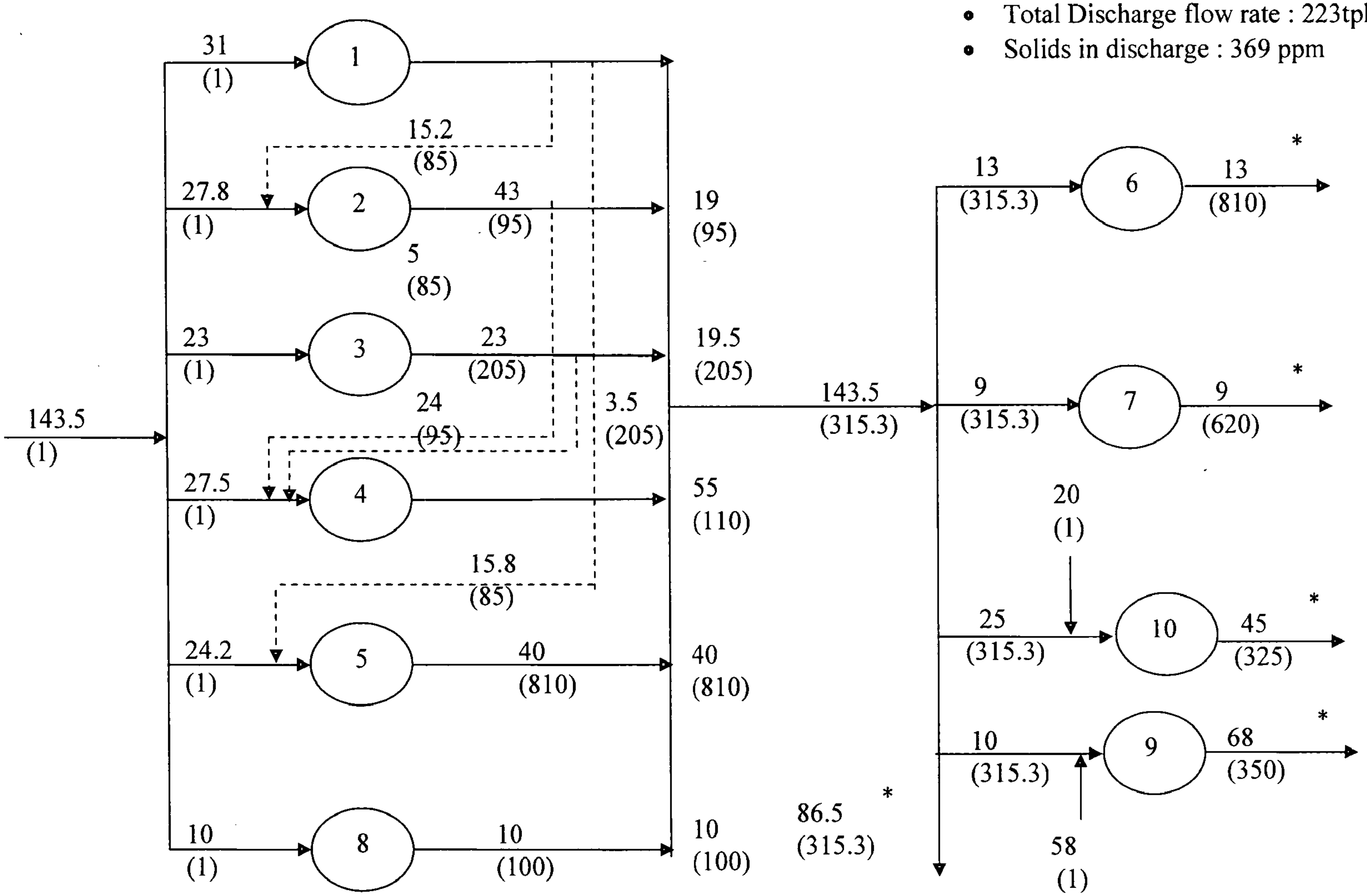


Fig. 5.14 Modified water network (*reuse* technique)

5.4 SALIENT RESULTS OF PROBLEM 3.4

Results & discussion

The initial study of the problem shows that by using the concept of reuse and recycle the water utilization can improve to a great extent and thus can decrease the waste water load on effluent treatment plant. The concept of regeneration has not been considered in the present study as it will require additional equipments.

The first step is to prepare water balance diagram of existing water using network. The next step is to use a heuristic approach to solve the problems using tools of concentration interval diagram, concentration composite curves and water supply lines to establish the minimum water flow rate in a multiple contaminant system. The next step is to investigate the feasibility of reusing the water leaving from one operation into another operation within the system. This involves shifting of the inlet & outlet concentration of operation in the plot of limiting water profiles as shown in **Fig. 5.15 to 5.19. Fig. 5.15** represents the limited water profiles for solid contaminant prior to concentration shifts where as **Fig. 5.16 to 5.19** shows how to determine concentrations of the contaminant (TDS) for reuse of water from outlets of Reactor 1 (R-1), Separators (S), Grinder (G) and Starch washing screen (SWS) respectively to other water using operations. Similar procedure is adopted for other contaminants such as TOC and TSS.

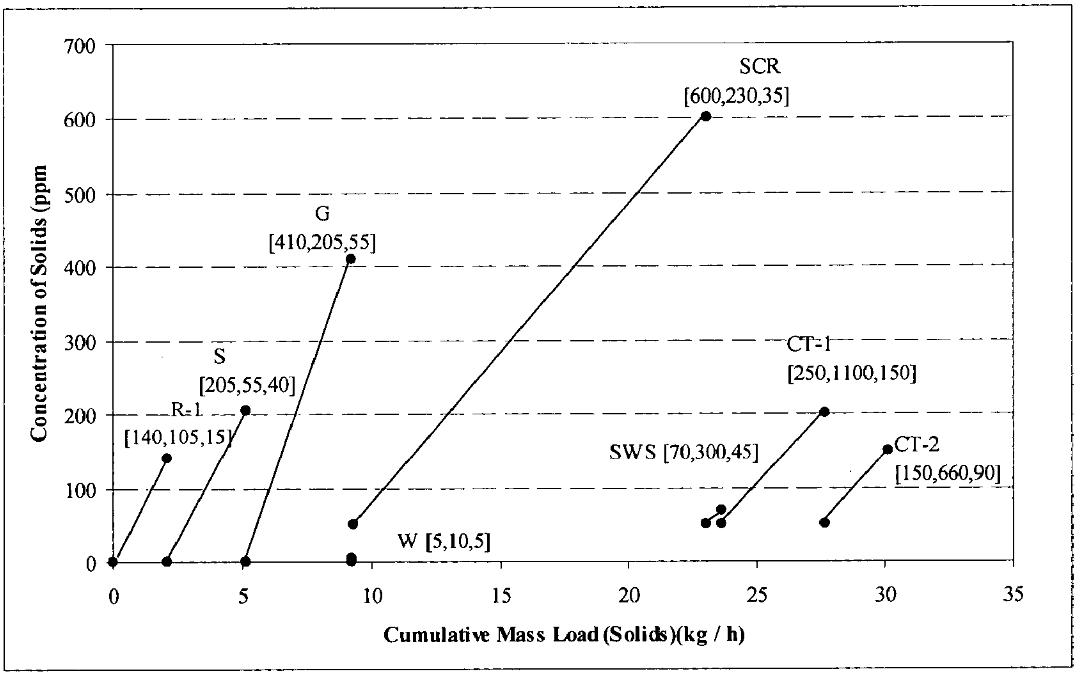


Fig. 5.15 Limited Water Profiles for each operation prior to concentration shifts

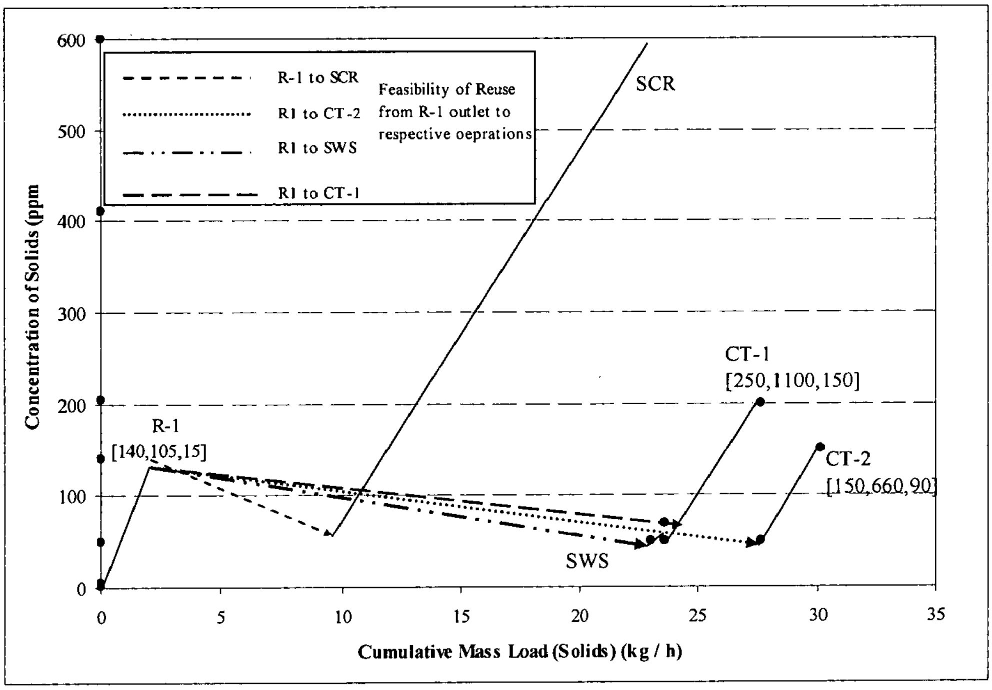


Fig. 5.16 Determination of the concentration of the contaminant Solids for reusing water from outlet of Reactor 1 (R-1) to other water using operations

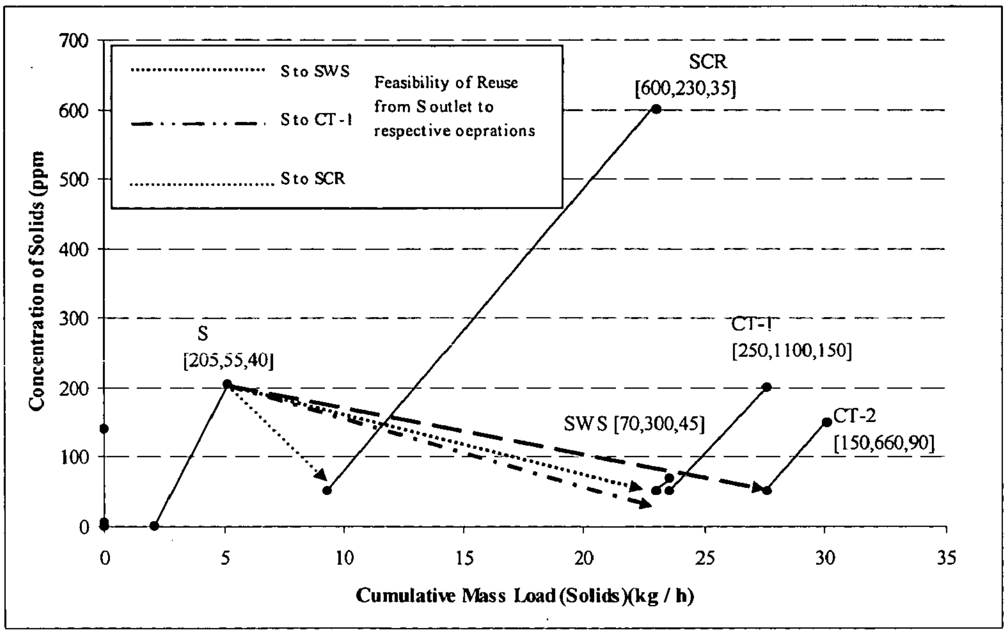


Fig.5.17 Determination of the concentration of the contaminant Solids for reusing water from outlet of Separators (S) to other water using operations

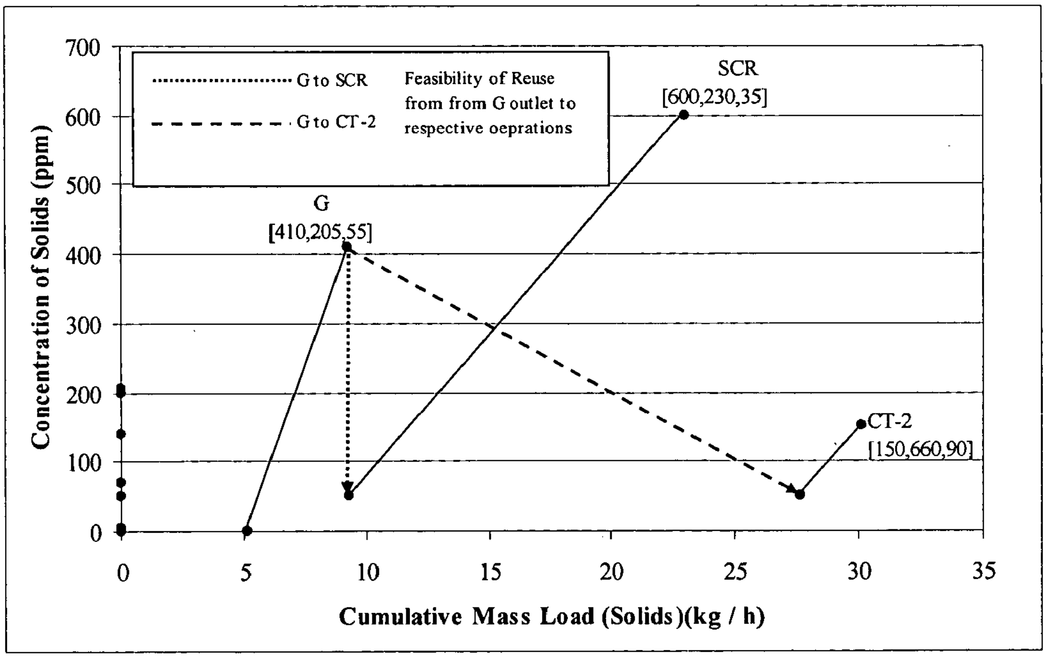


Fig. 5.18 Determination of the concentration of the contaminant Solids for reusing water from outlet of Grinding (G) to other water using operations

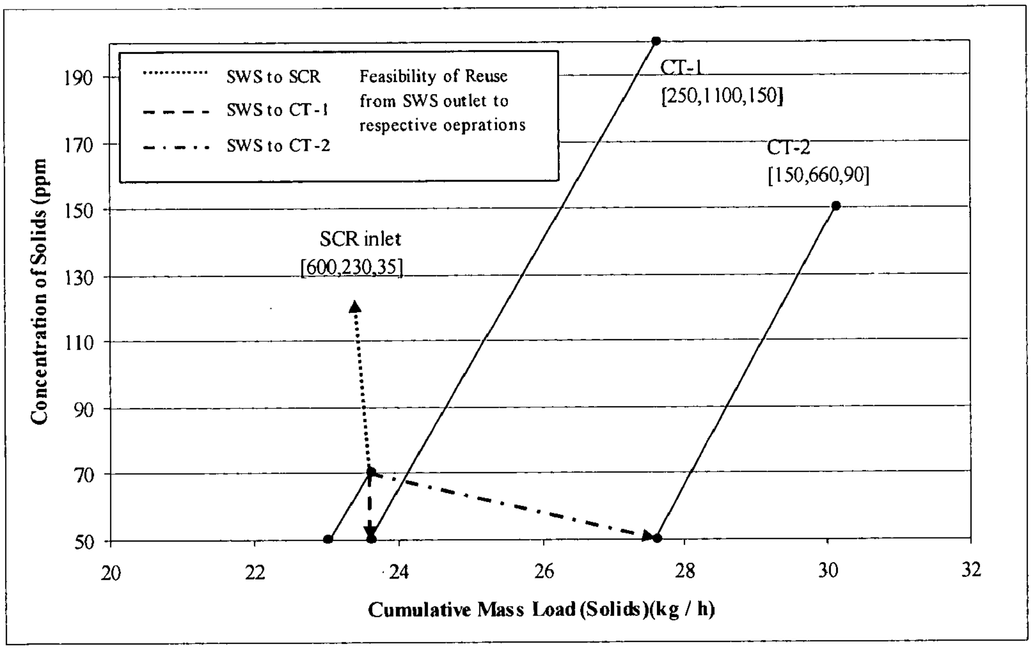


Fig. 5.19 Determination of the concentration of the contaminant Solids for reusing water from outlet of Starch washing screen (SWS) to other water using operations

Mass load and concentrations of contaminant (TDS) are determined for stream (R1, S, G and SWS) when these were reused in other operation as given in **Table 5.8.** Computed flow rates of different reused streams along with flow rates of other streams which were revised due the above reuse are shown in **Table 5.8.**

For other contaminants such as TSS and TOC similar computation were carried out and the corresponding concentrations of these contaminants in different streams are shown directly in **Fig. 5.20** which shows the new modified water using network. **Fig.5.21** represents the modified water network obtained through ASPEN WATER. The results obtained through ASPEN WATER are similar to those obtained through graphical techniques.

The detail calculation of cost benefit analysis has been explained in **section 6.5 of chapter 6.**

Table 5.8 Comparison of Operation wise water consumption pattern

Flow of water from respective unit to corresponding unit		Flow rate after modification (tph) (Graphical & Heuristic Approach)	Flow rate after modification (tph) (ASPEN WATER)	Flow rate before modification (tph)
DM water	Reactor 1	15	15	15
	Separators	15	15	15
	Grinding	0.5	0.46	9.804
	Washing	6	5.75	10.784
	Total	**36.5**	**36.21**	**50.00**
Fresh Water	Washing	5	3.597	0.000
	SWS	0.7	0.59	30.000
	CT-1	12.6	13.18	20.000
	CT-2	0	0	25.000
	Scrubber	12.1	11.90	25.000
	Total	**30.4**	**29.267**	**100.000**
Reactor1 Outlet	Sewer	0	0.000	15
	SWS	4.8	4.72	0.000
	CT-1	1.7	1.47	0.000
	CT-2	7	7.2	0.000
	Scrubber	1.5	1.61	0.000
	Total	**15**	**15**	**15**
Separators Outlet	Sewer	0	0.000	15
	SWS	1.5	1.643	0.000
	CT-1	0	0	0
	CT-2	12.5	12.22	0.000
	Scrubber	0.9	0.85	0.000
	Total	**15**	**14.71**	**15**
Grinding Mill Outlet	Sewer	0.4	0.000	10
	CT-2	1.6	1.715	0.000
	Scrubber	8	8.095	0.000
	Total	**10**	**9.810**	**10**
Washing Outlet	Grinding	9.5	9.348	0.000
	Washing Recirculation	1.5	1.437	0.000
	Sewer	0	0.000	11
	Total	**11**	**10.784**	**11**
SWS Outlet	Sewer	0	0.000	30
	SWS Recirculation	23.2	23.052	0.000
	CT-1	0.5	0.529	0.000
	CT-2	3.9	3.866	0.000
	Scrubber	2.4	2.556	0.000
	Total	**30**	**30.003**	**30**
CT-1 Blow down	Sewer	4	4.58	4.58
	Total	**4**	**4.58**	**4.58**
CT-2 Blow down	Sewer	2.8	3.226	8.5
	CoolTow1	5.2	5.107	0.000
	Total	**10**	**8.333**	**8.5**
Scrubber Outlet	Sewer	25	25.03	25
	Total	**25**	**25.03**	**25**

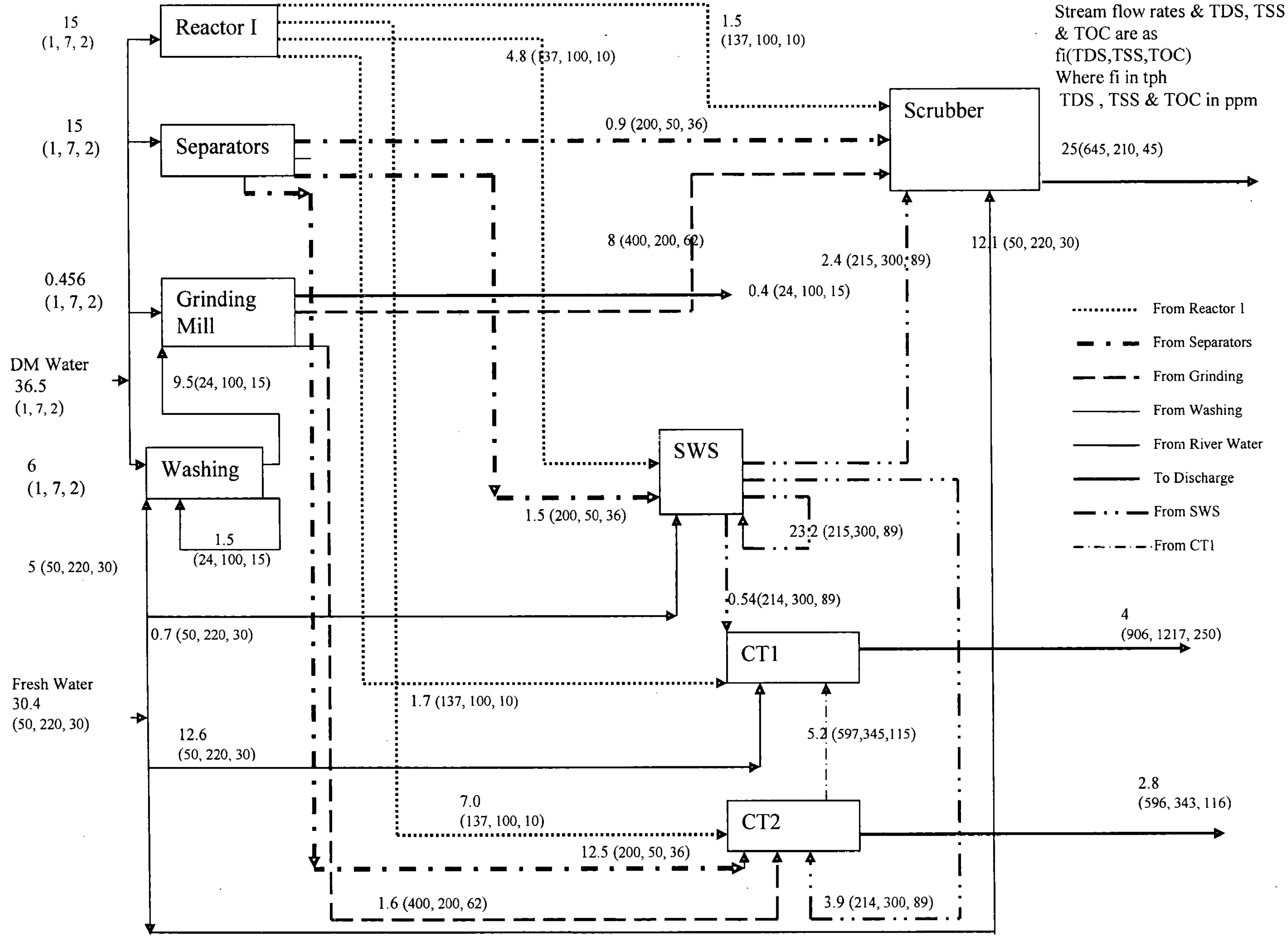
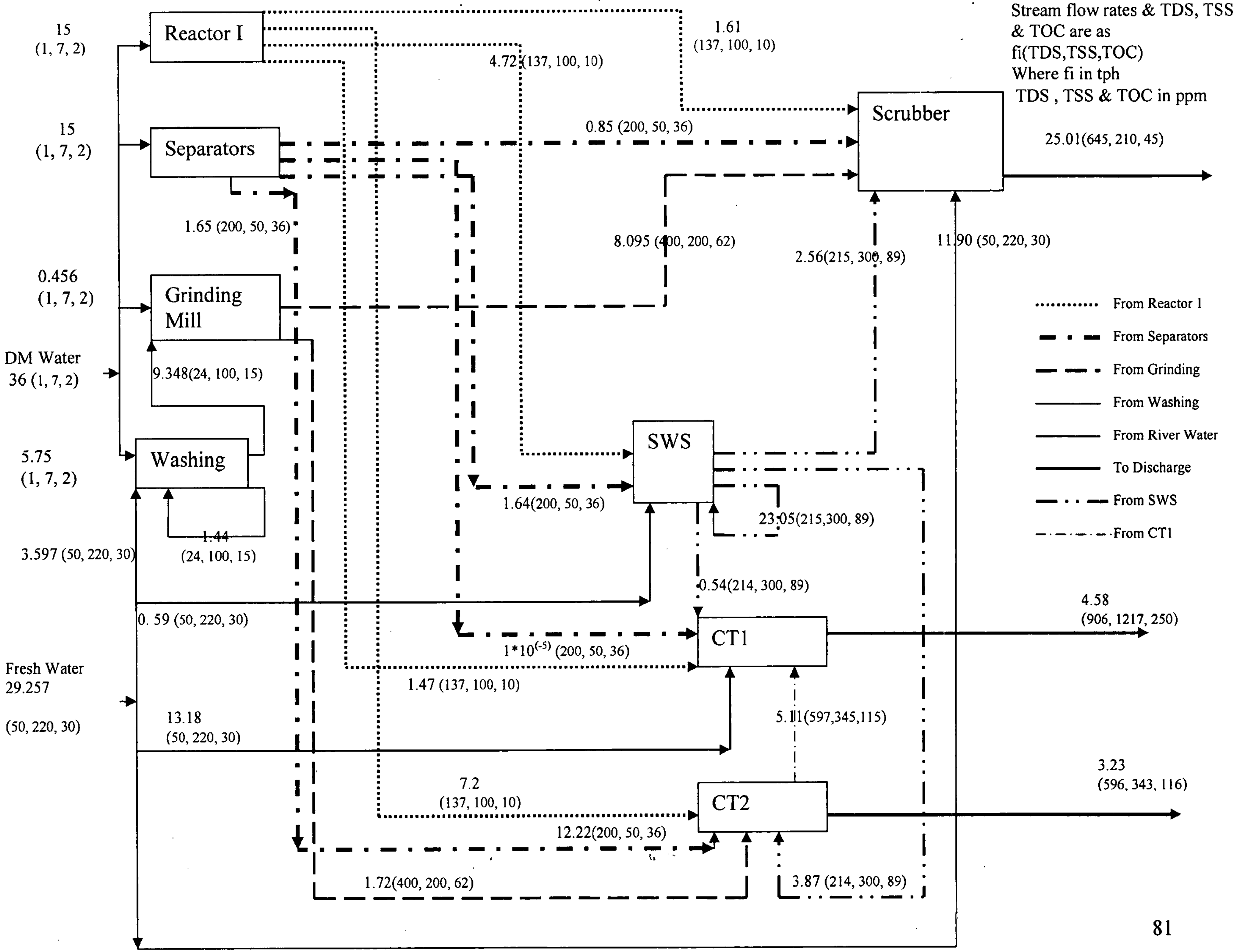


Fig. 5.20 Modified water network (*reuse* technique)


Stream flow rates & TDS, TSS & TOC are as fi(TDS,TSS,TOC)
Where fi in tph
TDS , TSS & TOC in ppm
Reactor I
Separators
Grinding Mill
Washing
SWS
Scrubber
CT1
CT2
15 (1, 7, 2)
15 (1, 7, 2)
0.456 (1, 7, 2)
DM Water 36 (1, 7, 2)
5.75 (1, 7, 2)
3.597 (50, 220, 30)
Fresh Water 29.257 (50, 220, 30)
1.61 (137, 100, 10)
4.72 (137, 100, 10)
0.85 (200, 50, 36)
25.01(645, 210, 45)
1.65 (200, 50, 36)
8.095 (400, 200, 62)
2.56(215, 300, 89)
11.90 (50, 220, 30)
9.348(24, 100, 15)
1.44 (24, 100, 15)
1.64(200, 50, 36)
23.05(215,300, 89)
0.54(214, 300, 89)
0. 59 (50, 220, 30)
4.58 (906, 1217, 250)
1*10(-5) (200, 50, 36)
1.47 (137, 100, 10)
13.18 (50, 220, 30)
5.111(597,345,115)
3.23 (596, 343, 116)
7.2 (137, 100, 10)
12.22(200, 50, 36)
1.72(400, 200, 62)
3.87 (214, 300, 89)
From Reactor 1
From Separators
From Grinding
From Washing
From River Water
To Discharge
From SWS
From CT1

5.5 SALIENT RESULTS OF PROBLEM 3.5

The initial observations of the case study shows that by properly integrating cooling tower with the cooling water network and readjusting the flow rates and inlet and exit temperatures individual units under the given constraints, the water utilization can be improved to a great extent and thus the fresh water consumption can be decrease considerably. The salient results obtained are discussed below:

5.1 Construction of CWCC for different sections of the network

The CWCC for all sections namely Furnace melting, neck section, refining and spout section and tin bath section are shown in **Fig. 5.23 and 5.24** respectively. During computation, three sections, namely, furnace melting, neck and refining-spout sections are merged together and a single composite curve and a single modified water network has been developed for these sections. The allowable discharge temperature from the network is 41 °C. This is the temperature at which the warm water enters the cooling tower. The targeted maximum flow rate of cooling water computed based on pinch temperature of the three sections namely, furnace melting, neck - refining -spout section and tin bath section are 380.2, and 588 tph respectively.

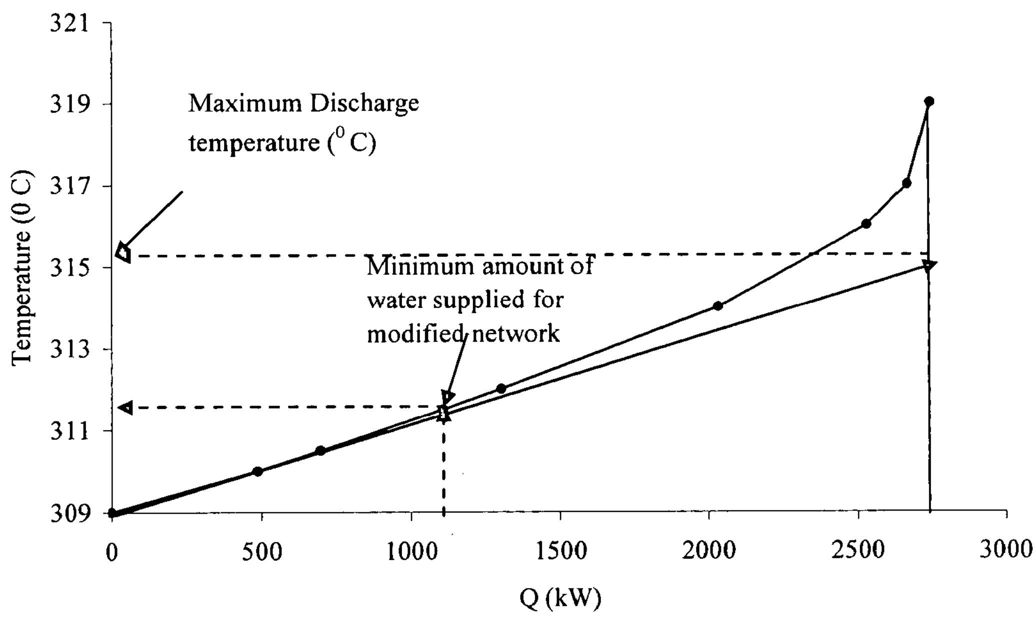


Fig.5.22 CWCC for combining Furnace melting, Neck and Refining-spout section

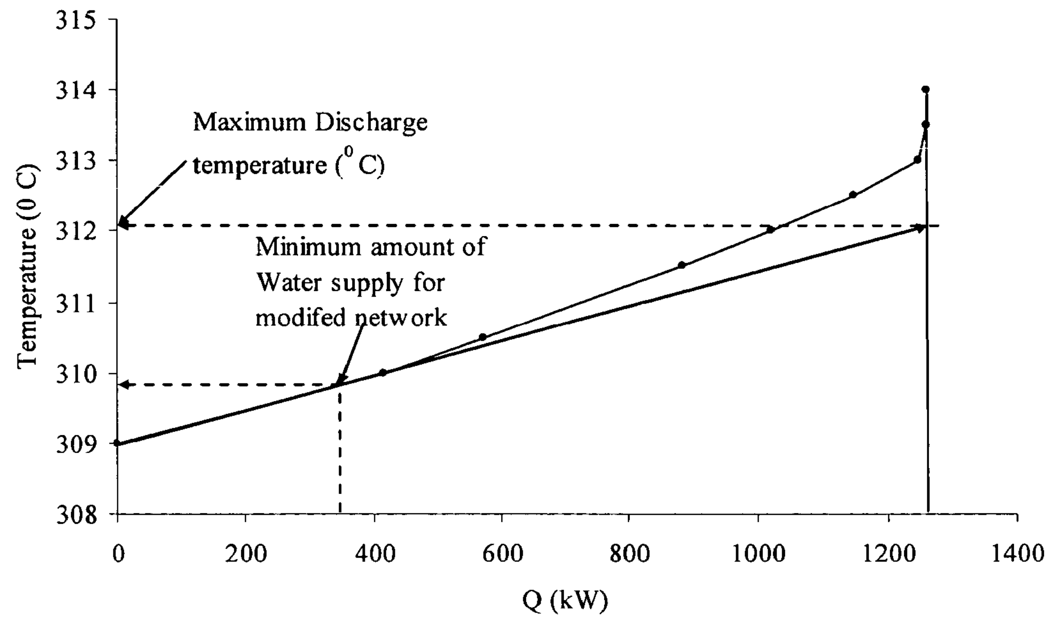


Fig. 5.23 CWCC for combining Tin bath section

5.2 Design Procedure

The design procedure described by Kim and Smith (2001) is applied to all the three section, taking in to account the constraints of minimum water supply line and discharge water temperature. Two different strategies had been worked out considering variation of fresh water supply temperature in summer and winter. The cost benefit analysis has been explained in Chapter 6. **Fig. 5.25 to 5.28** represents the modified water network for different proposals in case of summer season. **Fig.5.29 to 5.32** represents the modified water network for different proposal in case of winter season. **Fig.5.33 and Fig.5.34** represents the existing and modified water networks for furnace melting, neck and refining-spout section. **Fig. 5.35 and Fig. 5.36** represents the existing and modified water networks for tin bath section.

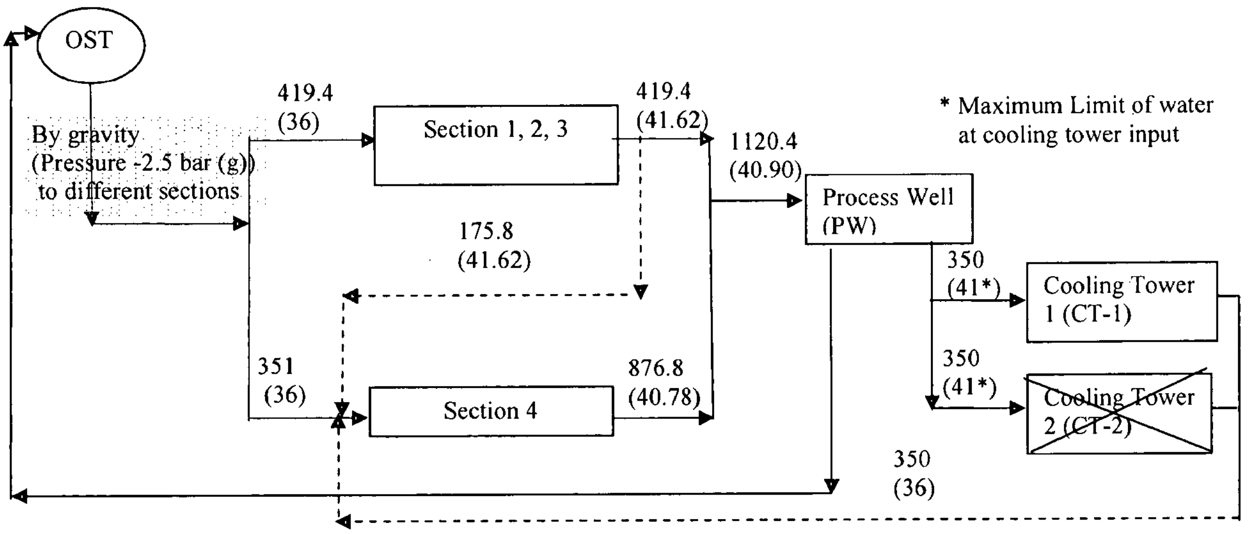


Fig. 5.24 Proposal 1-A: Modification of water network based on utilization of cooling tower directly to process plant section and reuse from one section to anothe section

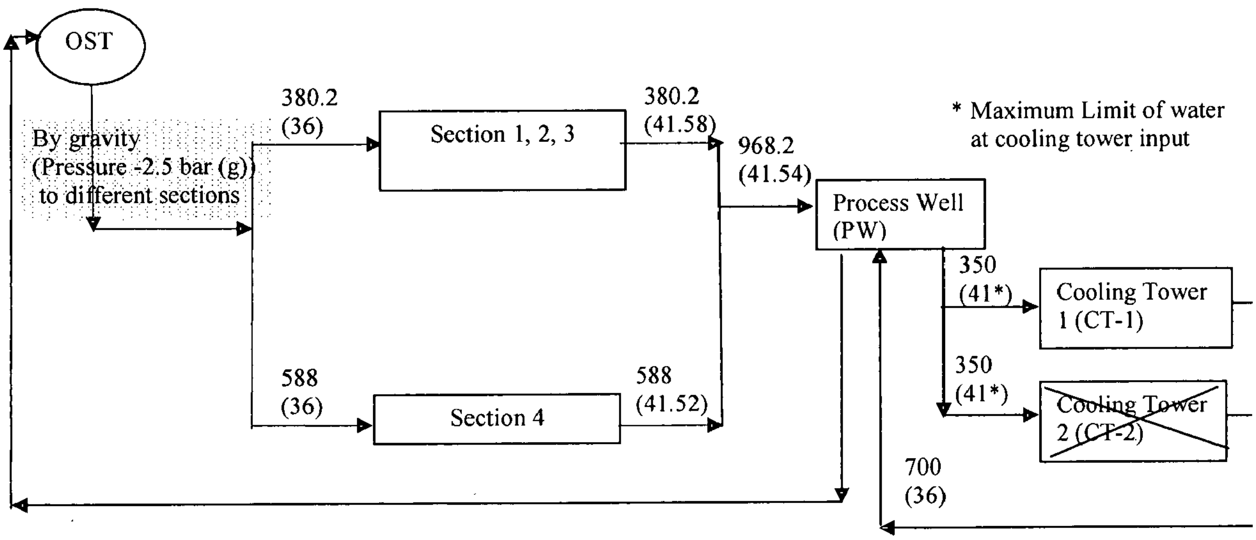


Fig.5.25 Proposal 2-A: Modification of water network based on water pinch technology

Note: *Values shown without brackets are flow rates of cooing water in tph where as value within small brackets are temperature in (^{0} C)*

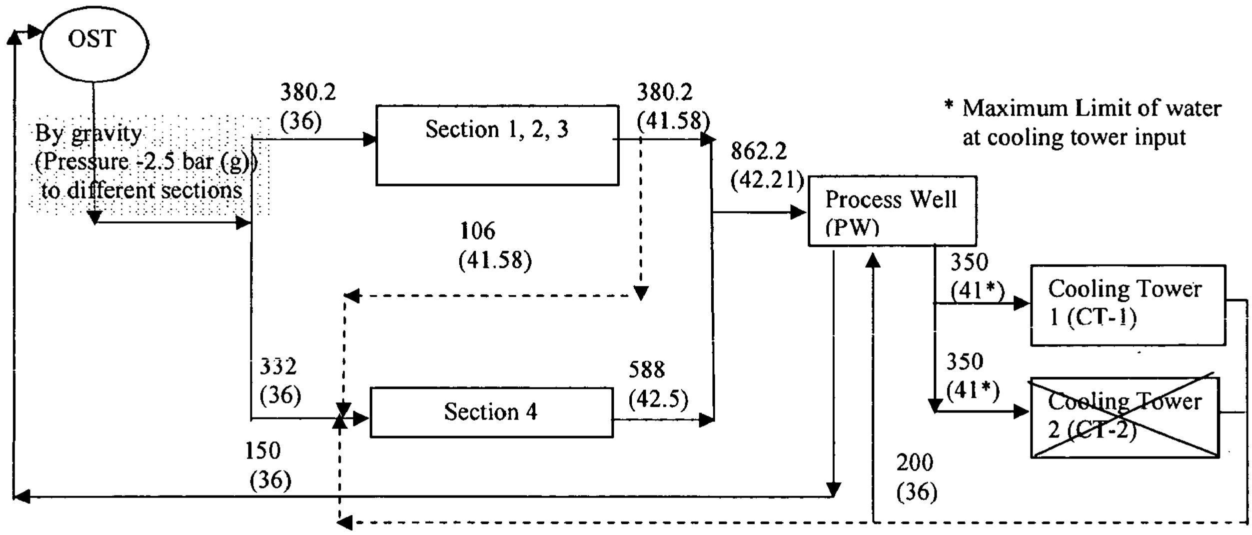


Fig. 5.26 Proposal 2 A (Special Case 1):

Modification of water network based on water pinch technology and utilization of cooling tower directly to process plant section and reuse from one section to another section

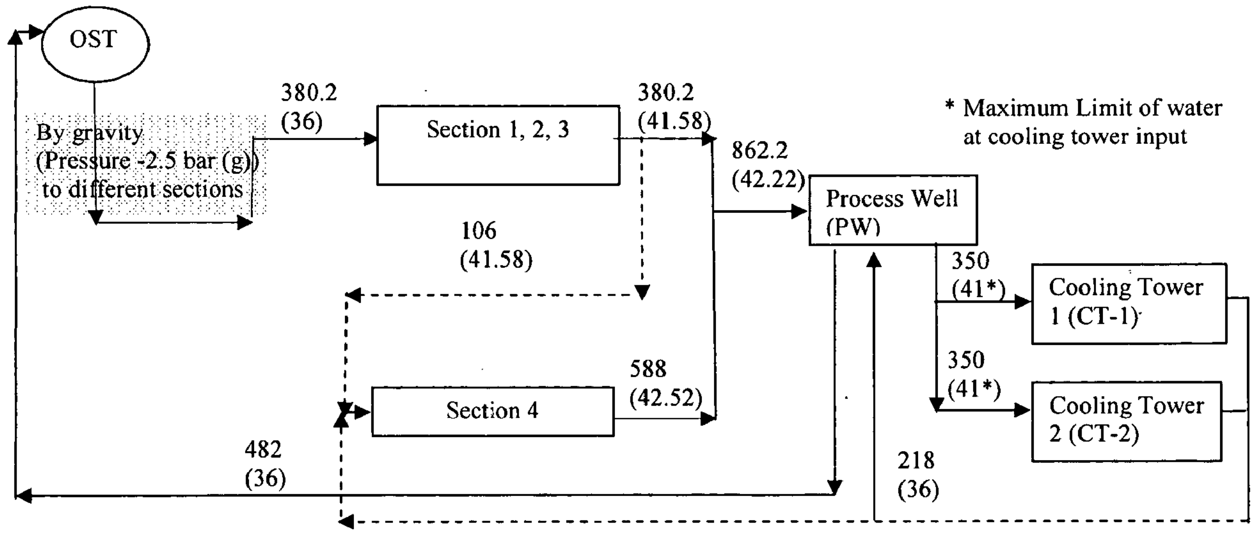


Fig. 5.27 Proposal 2A (Special Case 2):

Modification of water network based on water pinch technology and utilization of cooling tower directly to process plant section and reuse from one section to another section and simultaneous operation of two cooling towers.

Note: *Values shown without brackets are flow rates of cooing water in tph where as value within small brackets are temperature in (^{0} C)*

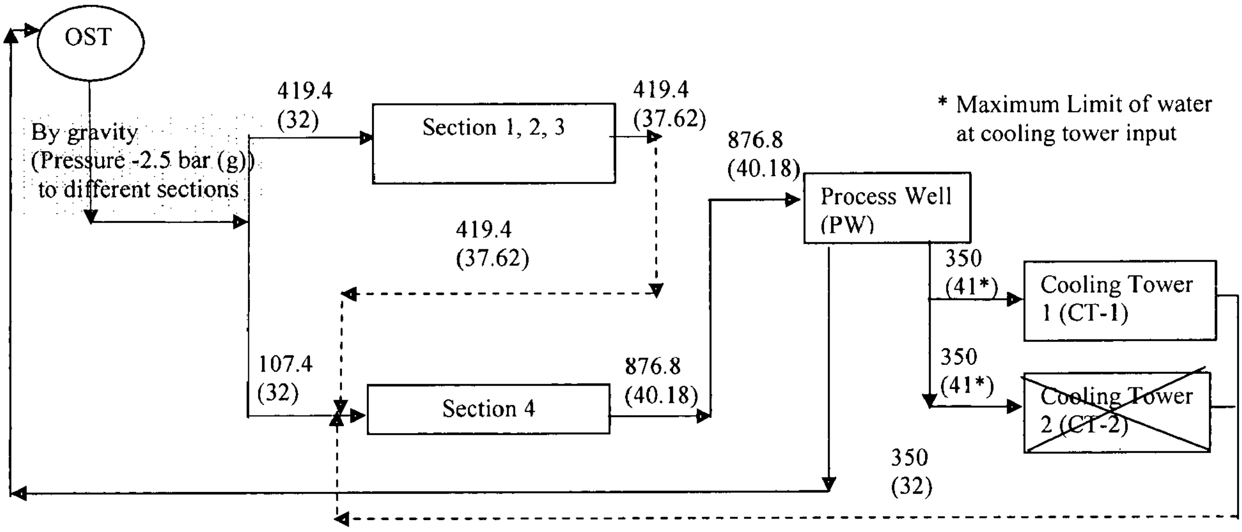


Fig. 5.28 Proposal 1-B:
Modification of water network based on utilization of cooling tower directly to process plant section and reuse from one section to another section

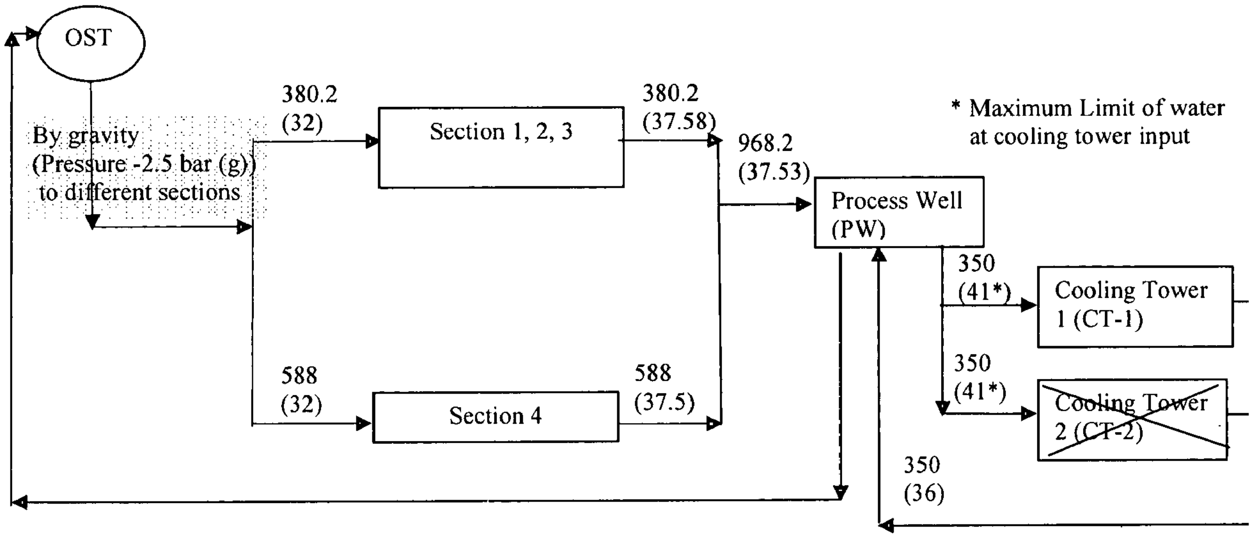


Fig. 5.29 Proposal 2 B: Modification of water network based on water pinch technology

Note: *Values shown without brackets are flow rates of cooing water in tph where as value within small brackets are temperature in (^{0} C)*

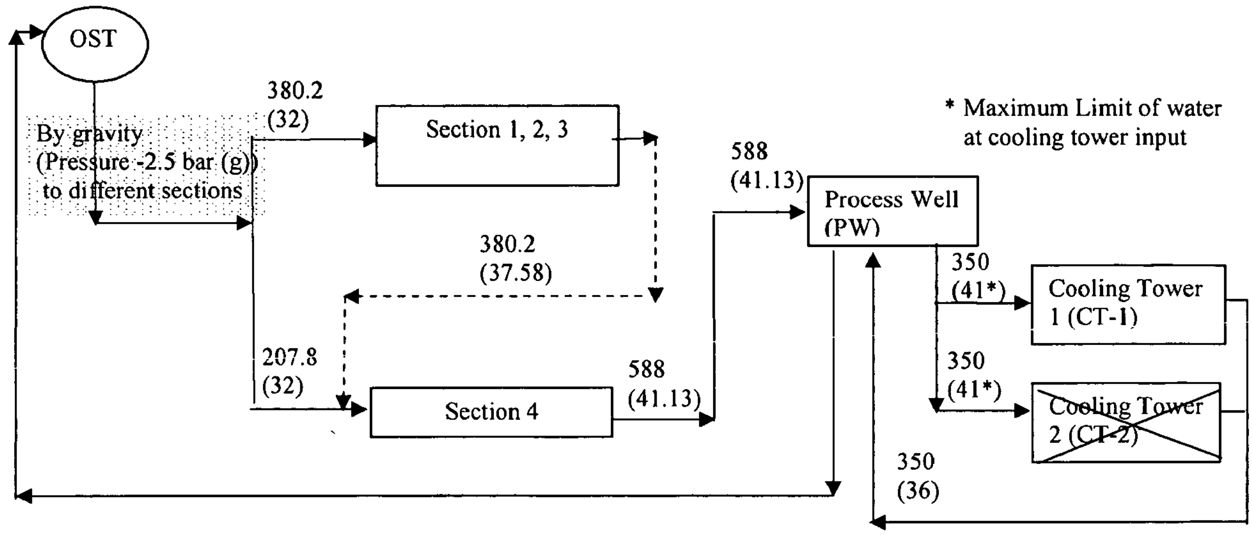


Fig. 5.30 Proposal 2 B (Special Case 1): Modification of water network based on water pinch technology and reuse from one section to another section

Note: *Values shown without brackets are flow rates of cooing water in tph where as value within small brackets are temperature in (^{0} C)*

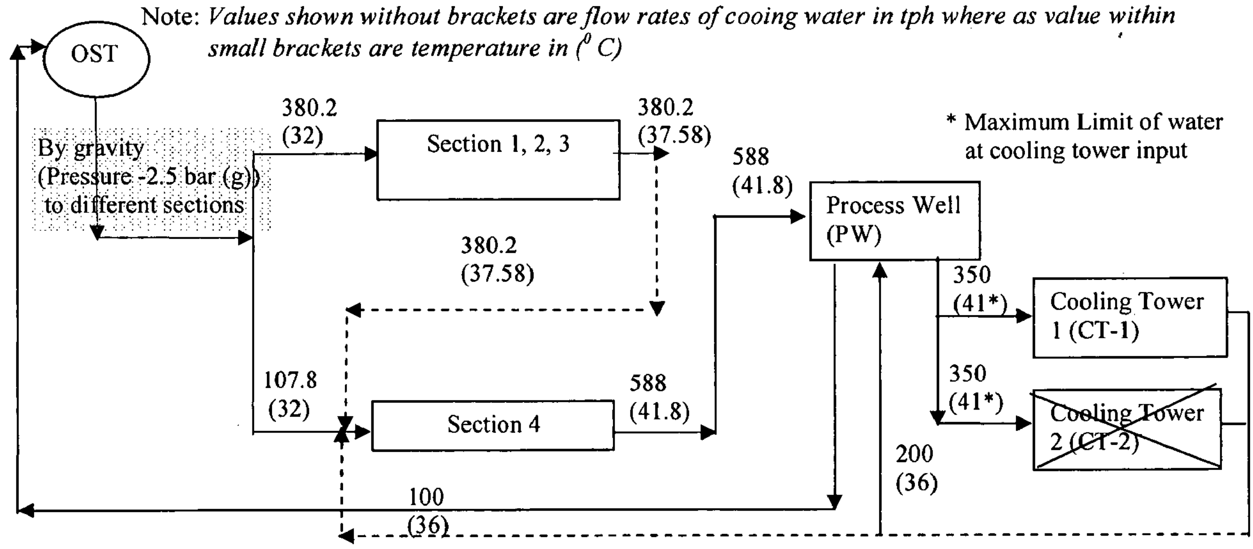


Fig. 5.31 Proposal 2 B (Special Case-2)
Modification of water network based on water pinch technology and utilization of cooling tower directly to process plant section and reuse from one section to another section

Note: *Values shown without brackets are flow rates of cooing water in tph where as value within small brackets are temperature in (^{0} C)*

The detail calculation of cost benefit analysis has been explained in **section 6.6 of chapter 6.**

Note: *Values shown without brackets are flow rates of cooing water in tph where as value within small brackets are temperature in (^{0}C)*

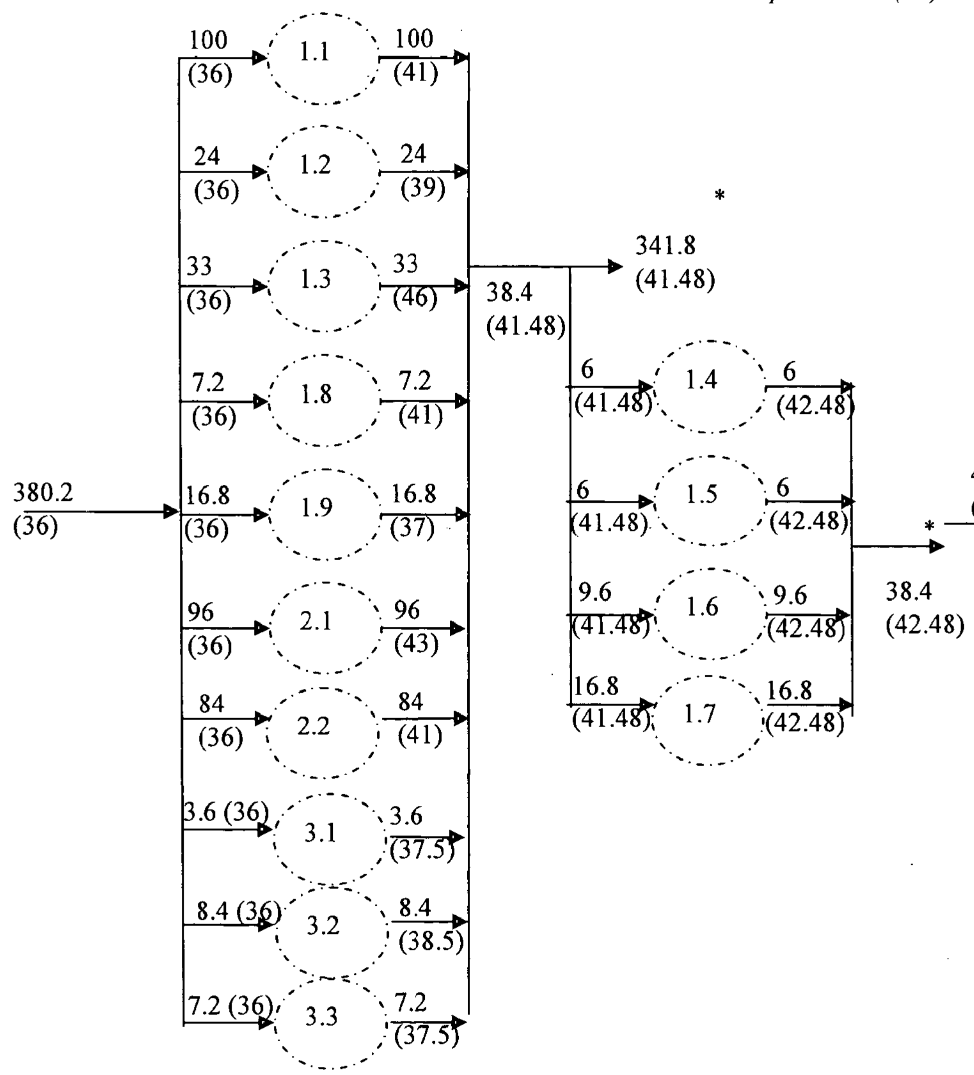


Fig 5.33 Modified water network for furnace melting, neck and refining –spout section

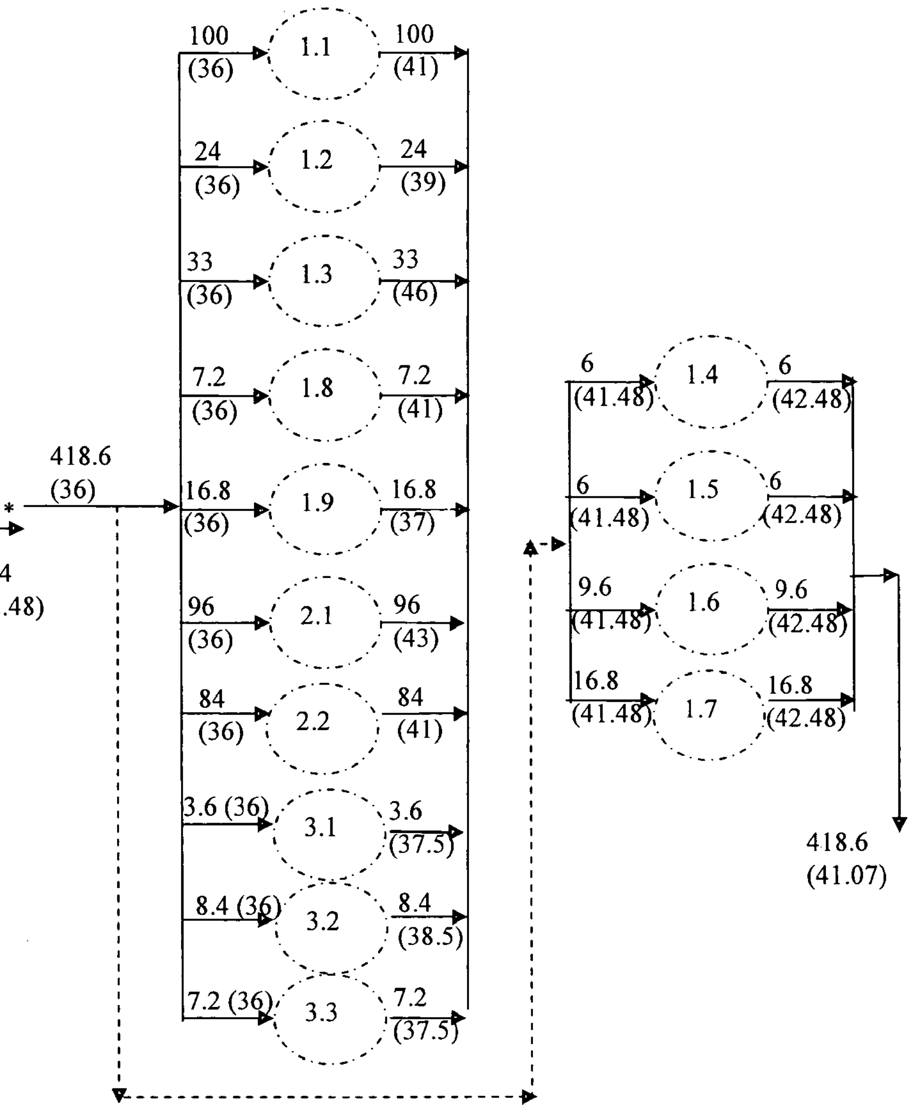


Fig 5.32 Existing water network for furnace melting, neck and refining –spout section

Note: *Values shown without brackets are flow rates of cooing water in tph where as value within small brackets are temperature in (⁰ C)*

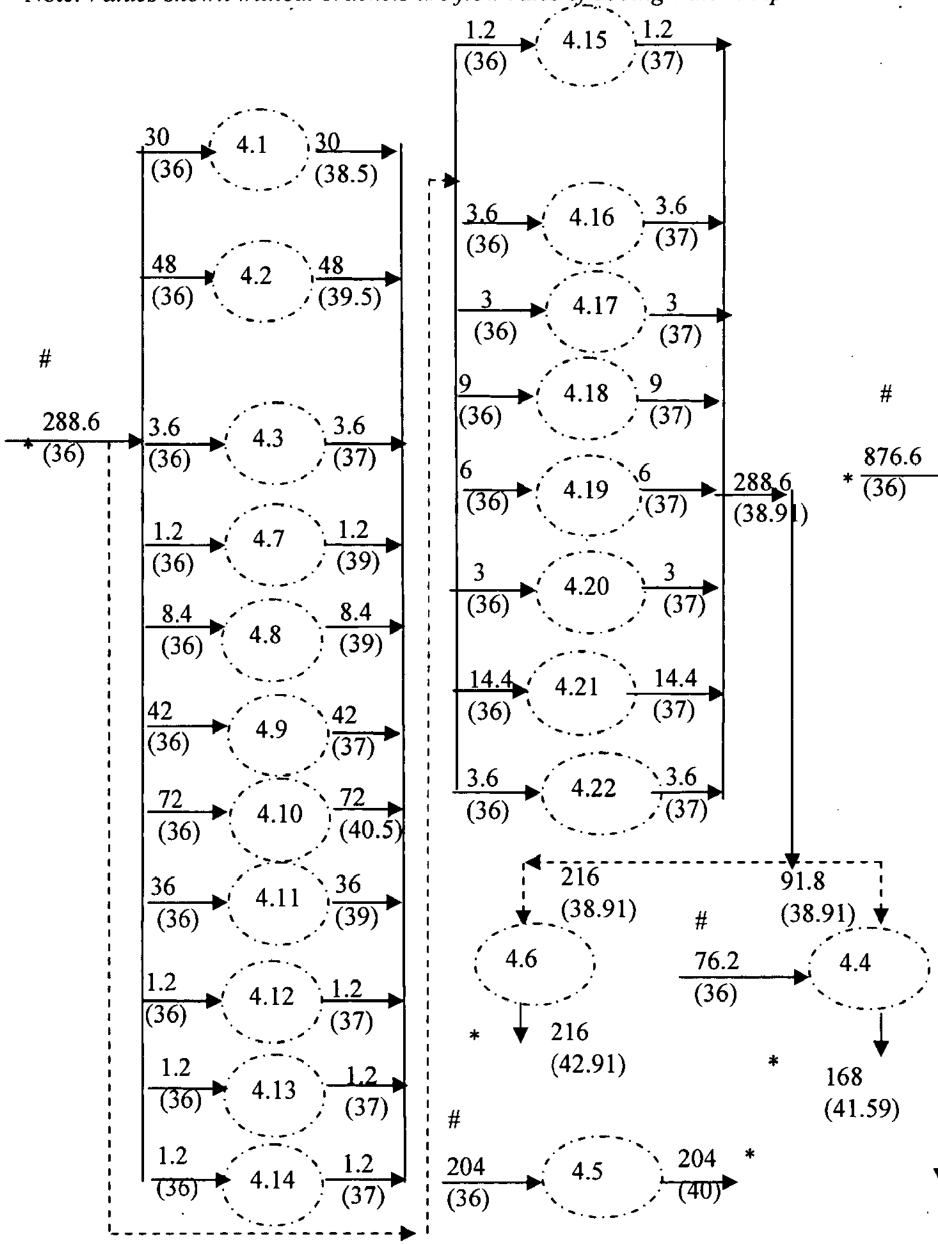


Fig 5.35 Modified water network for tin bath section

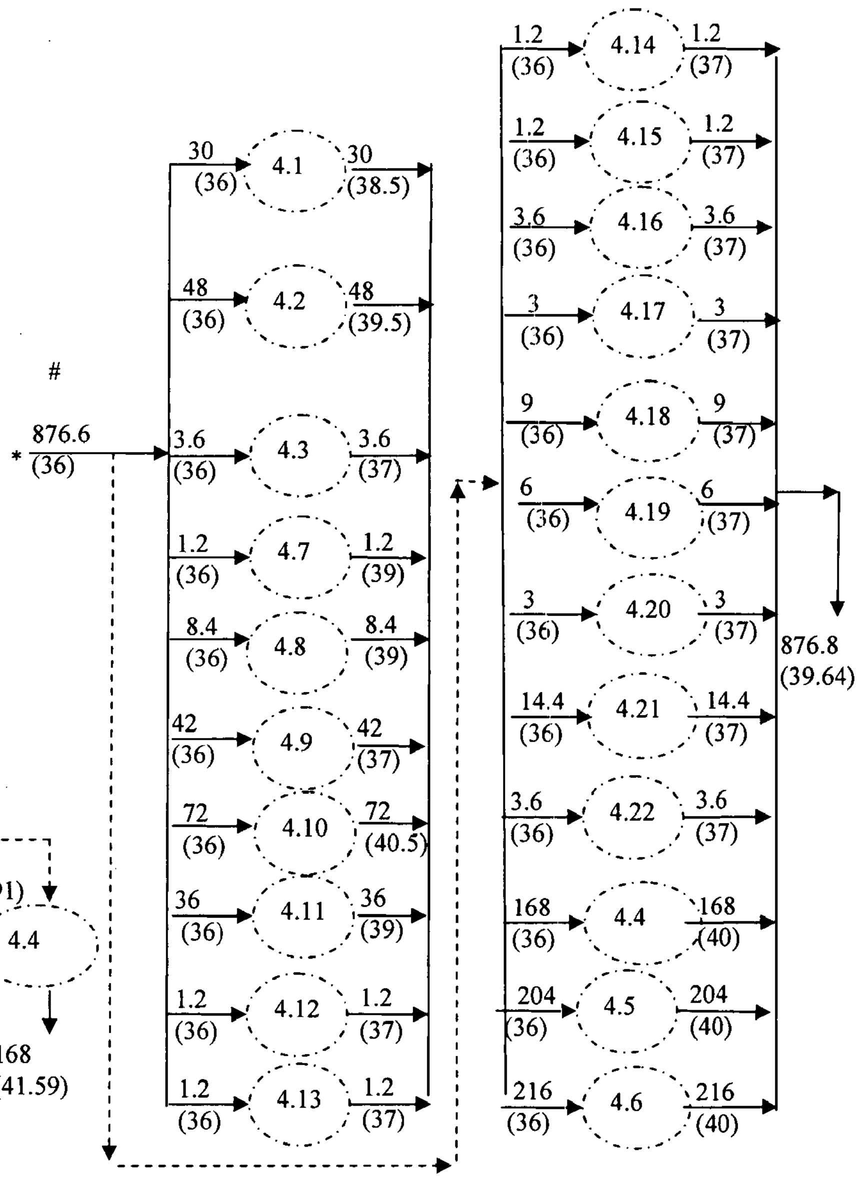


Fig 5.34 Existing water network for tin bath section

CHAPTER 6

COST- BENEFIT ANALYSIS

6.1 Cost Analysis

The cost analysis is an important part before implementation of any modification in the existing water network. This section of paper explains detail cost computation of existing water networks as well as modified water network as discussed in previous chapters. Since the concept of water pinch technology requires alteration in existing piping lay out and installation of new equipment for *regeneration-reuse and regeneration recycling* techniques, the basic information are required to be gathered from existing piping network are presented in APPENDIX B:

Table 6.1 Useful Table to compute cost benefit analysis

Specifications	Problem 3.1	Problem 3.2	Problem 3.3	Problem 3.4	Problem 3.5
Detail piping layout of existing water network	B.3.1.1	B.3.2.1	B.3.3.1	B.3.4.1	B.3.5.1
Details of pump and power consumption of existing water transfer pump	B.3.1.2	B.3.2.2	B.3.3.2	B.3.4.2	B.3.5.2
Piping cost per unit m length for different sizes	Table B.1				
Fittings, accessories and erection commissioning cost	Table B.2				
Distance from new proposed regeneration unit to existing units	B.3.1.3	B.3.2.3	-	B.3.4.3	-
Distance between existing units	-	-	B.3.3.3	-	-

6.2 Salient Results of Cost Analysis of Problem 3.1

6.2.1 Benefit Analysis

Table 6.2 represents the benefit of water pinch technology. It compares modified water using networks with that of existing ones for present case study. It also represents the net savings in water based on the modifications. It can be observed that the water-pinch analysis reduced the consumption of DM water to a considerable extent. ASPEN WATER has been used to evaluate the selected network. ASPEN WATER uses mathematical programming approach based on MINLP. The results obtained from ASPEN WATER for all three cases i.e. *reuse*, *regeneration-reuse* and *regeneration –recycling* are reported in Table 6.2. The results obtained from graphical method and that from ASPEN WATER are almost similar. It should be noted that the optimal networks suggested by ASPEN WATER are slightly different than those suggested by Graphical Technique in terms of water flow rates in different units.

Thus it can be safely concluded that Graphical approach provides accurate results and comparable with the results obtained from ASPEN WATER software and thus can be implemented in the industry.

Table 6.2 Benefits of water pinch technology (Problem 3.1)

	Before Analysis	After Analysis					
		reuse	*reuse* (ASPEN WATER)	*regeneration -reuse*	*regeneration -reuse* (ASPEN WATER)	*regeneration - recycling*	*regeneration - recycling* (ASPEN WATER)
DM Water (tph)	50	31.9	31.2	21.57	22	12	12
% Savings in DM Water	0	36.1	37.58	56.82	56	76	76
Waste Water generation (tph)	50	31.9	31.2	14	14	12	12
Concentration of Solids (ppm)	76	118.9	107	40	40	241	259

6.2.2 Cost Analysis

The basis of costing is very important for carrying out cost analysis. **Table 6.3** presents the power comparison of different modified water network with existing water network. **Table 6.4** represents piping cost per unit m length for different sizes. **Table 6.4** shows the cost of different modified water networks such *reuse, regeneration-reuse* and *regeneration-recycling* along with existing water network. It has been prepared by considering various data presented as shown in Appendix B. **Table 6.4** represents the comparison of cost of water networks based on changes in flow rate of DM water, changes in pipe sizes and thus necessary cost associated with piping layout (i.e. civil, structural, erection and commissioning cost).

Table 6.3 Power consumption comparison of different modified water network with existing water network

Specifications	*Existing*	*Reuse*	*Regeneration-Reuse*	*Regeneration-Recycling*
Pump Capacity (delivered) (m^3/ h)	50	31.9	21.57	12
Pump Head (delivered) (m)	30	30	30	30
Efficiency of pump (%)	60	65	65	65
Power consumption (kW)	6.81	4.02	2.72	1.51
Power consumption (hp)	9.12	5.39	3.64	2.02
Motor efficiency (%)	90	90	90	90
Current drawn at full capacity (amp)	19.1	11.29	7.62	4.23
Power consumption (kW)	7.56	4.47	3.01	1.68
No. of unit per hour (kW-h)	7.56	4.47	3.01	1.68
Cost of power (INR / unit)	4	4	4	4
Total cost of power consumption (INR per hour)	2,64,902	1,56,628	1,05,470	58,867
Operating hours	24	24	24	24
No. of operating days	365	365	365	365

Table 6.4 Cost comparison of different modified network with exiting network

Total Cost of network	*Existing*	*Reuse*	*Regeneration-Reuse*	*Regeneration-Recycling*
Fixed cost of centrifugal pump	35,000	25,000	25,000	31,000
Fixed cost of electric motor	10,000	8,000	7,000	12,000
Fixed cost of Base plate + accessories +Civil foundation of centrifugal pump	5,000	4,500	4,000	8,000
Fixed cost of piping layout from DM water storage tank to plant storage tank	14,700	14,700	3,675	14,700
Fixed cost of accessories for piping layout	1,470	1,470	368	1,470
Break up of erection and commissioning cost of piping layout				
(1) Cost of civil work	1,470	1,470	368	1,470
(2) Cost of welding work	1,176	1,176	294	1,176
(3) Cost of piping layout work	2,205	2,205	551	2,205
(4) Support Structure for pipeline layout	368	368	92	367
Total cost of electrical panel, cables etc.	28,000	25,000	18,000	19,000
Total cost of piping layout from FWM to other units as per existing and modified networks	1,94,04	19,404	19,404	19,404
Total cost of piping layout from D to other units as per existing and modified networks	32,340	38,808	29,106	25,872
Total cost of piping layout from SCR to other units as per existing and modified networks	48,510	40,425	38,808	64,680
Total cost of piping layout from G to other units as per existing and modified networks	25,872	42,042	42,042	23,931
Fixed cost of discharge header from plant to ETP sump	14,250	14,250	19,000	19,000
Fixed cost of valves	9,000	9,000	9,000	9,000
Fixed cost of instrumentation	1,29,500	1,29,500	1,29,500	1,29,500
Total Cost of existing network (INR)	***3,78,265***	***3,77,318***	***3,46,207***	***3,82,775***
Cost of regeneration equipments(INR)	-	-	***7,85,000***	***8,50,000***

Further, it can observed that due to the decrease in flow rate of DM water consumption, load on DM water plant has also been decreased and this will result in decrease in operating cost of DM water plant. However the present problem is a retrofit case this decrease in fixed cost of DM water plant is not considered. **Table 6.5** illustrates the fixed capital investment, cost of additional equipment, profit incurred in operating cost in case of base case (existing network), *regeneration-reuse* and *regeneration-recycling.* For the case of *reuse* there is no extra fixed cost involved as it will use the hardware existing network. However, due to the changes made in the flow of water it will save an amount 22, 01,914 INR per year. From the **Table 6.5** it is clear that the computed payback period for the case of *regeneration-reuse* and *regeneration-recycling are* merely 2.5 and 2.3 months respectively which is very attractive.

Table 6.5: Fixed cost, operating cost, profits and payback periods of different modes of water conservation

Specifications	**Existing water network**	**Modified water network based on *regeneration-reuse* technique**	**Modified water network based on *regeneration-recycling* technique**
Fixed Capital Investments (INR)	3,78,265	11,31,707	8,54,512
Operating Cost per year (INR/year)	53,01,902	18,00,180	9,52,387
Service Life (years)	10	10	10
Total additional cost of capital investment due to installation of regeneration equipments (INR)	--	7,53,443	8,54,512
Total annual profit in operating cost per year (INR/year)	--	35,01,722	43,49,515
Payback period (months)	--	2.5	2.3

6.3 Salient results of cost analysis of PROBLEM 3.2

6.3.1 Benefit Analysis

Table 6.6 represents the benefit of water pinch technology. It compares modified water using networks with that of existing ones for present case study. It also represents the net savings in water consumption. It can be observed that the water-pinch analysis reduced the consumption of DM water to a considerable extent.

Table 6.6 Benefits of water pinch technology (Problem 3.2)

	Before Analysis	*reuse*	*regeneration-reuse*	*regeneration-recycling*
DM Water (tph)	69	59.83	34.5	30
% Savings in DM Water	--	13.3 %		27.5%
Concentration of Solids (ppm)	76	225.8	351.76	296.4

6.3.2 Cost Analysis

The basis of costing is very important for carrying out cost analysis. **Table 6.7** presents the power comparison of different modified water network with existing water network. **Table 6.8** shows the cost of different modified water networks such *reuse, regeneration-reuse* and *regeneration-recycling* along with existing water network. It has been prepared by considering various data presented as shown in Appendix B. **Table 6.8** represents the comparison of cost of water networks based on changes in flow rate of DM water, changes in pipe sizes and thus necessary cost associated with piping layout (i.e. civil, structural, erection and commissioning cost).

Table: 6.7 Power consumption comparison of different modified water network with existing water network

Specifications	*Existing*	*Reuse*	*Regeneration-Reuse*	*Regeneration-Recycling*
Pump Capacity (delivered) (m^3/ h)	69	59	34.5	30
Pump Head (delivered) (m)	30	30	30	30
Efficiency of pump (%)	65	65	65	65
Power consumption (kW)	8.8	7.42	4.33	3.77
Motor efficiency (%)	90	90	90	90
Current drawn at full capacity (amp)	28	21	13	11
Power consumption (kW)	9.8	8.3	4.9	4.1
No. of unit per hour (kW-h)	9.8	8.3	4.9	4.1
Cost of power (INR / unit)	4	4	4	4
Total cost of power consumption (INR per hour)	3,43,392	2,90,832	1,71,696	1,43,364
Operating hours	24	24	24	24
No. of operating days	365	365	365	365

Table 6.8 Cost comparison of different modified network with exiting network

Total Cost of network	*Existing*	*Reuse*	*Regeneration-Reuse*	*Regeneration-Recycling*
Fixed cost of centrifugal pump	45,000	45,000	28,000	28,000
Fixed cost of electric motor	15,000	15,000	7,000	7,000
Fixed cost of Base plate + accessories +Civil foundation of centrifugal pump	7,500	7,500	4,000	4,000
Fixed cost of piping layout from DM water storage tank to plant storage tank	14,700	980	980	14,700
Fixed cost of accessories for piping layout	1,470	14,700	14,700	1,470
Break up of erection and commissioning cost of piping layout				
(1) Cost of civil work	1,470	1,470	1,470	1,470
(2) Cost of welding work	1,176	1,176	1,176	1,176
(3) Cost of piping layout work	2,205	2,205	2,205	2,205
(4) Support Structure for pipeline layout work	368	368	368	368
Total cost of electrical panel, cables etc.	26,000	25,000	18,000	18,000
Total cost of piping layout from PS-I to other units as per existing and modified networks	29,106	38,808	29,106	29,106
Total cost of piping layout from PS-II to	32,340	42,042	32,340	32,340

other units as per existing and modified networks				
Total cost of piping layout from R to other units as per existing and modified networks	72,765	77,616	63,063	63,063
Total cost of piping layout from DW to other units as per existing and modified networks	25,872	25,872	25,872	25,872
Total cost of piping layout from S-4 to other units as per existing and modified networks	12,936	12,936	12,936	12,936
Fixed cost of discharge header from plant to ETP sump	19,000	19,000	18,050	18,050
Fixed cost of valves	11,000	11,000	11,000	11,000
Fixed cost of instrumentation	1,69,500	1,69,500	1,69,500	1,69,500
Total Cost of existing network (INR)	***4,87,408***	***5,10,173***	***4,39,766***	***4,40,256***
Cost of regeneration equipments(INR)	-		***7,85,000***	***8,50,000***

Further, it can observed that due to the decrease in flow rate of DM water consumption, load on DM water plant has also been decreased and this will result in decrease in operating cost of DM water plant. However the present problem is a retrofit case this decrease in fixed cost of DM water plant is not considered. **Table 6.9** illustrates the fixed capital investment, cost of additional equipment, profit incurred in operating cost in case of base case (existing network), *regeneration-reuse* and *regeneration-recycling.* For the case of *reuse* there is no extra fixed cost involved as it will use the hardware existing network. However, due to the changes made in the flow of water it will save an amount 17, 63,914 INR per year. From the **Table 6.9** it is clear that the computed payback period for the case of *regeneration-reuse* and *regeneration-recycling are* merely 1.8 and 1.1 months respectively which is very attractive.

Table 6.9 **Fixed cost, operating cost, profits and payback periods of different modes of water conservation**

Specifications	**Existing water network**	**Modified water network based on *regeneration-reuse* technique**	**Modified water network based on *regeneration-recycling* technique**
Fixed Capital Investments (INR)	81,71,363	32,51,297	27,85,893
Operating Cost per year (INR/year)	81,22,622	31,27,30	26,86,867
Service Life (years)	10	10	10
Total additional cost of capital investment due to installation of regeneration equipments (INR)	--	7,52,358	50,28,48
Total annual profit in operating cost per year (INR/year)	--	49,95,302	54,35,755
Payback period (months)	--	1.8	1.1

6.4 Salient results of cost analysis of PROBLEM 3.3

6.4.1 Benefit Analysis

Table 6.10 represents the benefit of water pinch technology. It compares modified water using networks with that of existing ones for present case study. It also represents the net savings in water consumption and load on effluent treatment plant based on the modifications. It can be observed that the water-pinch analysis reduced the consumption of DM water as well as fresh water to a considerable extent. For the above case study the flow rate of DM water is reduced by 28% and that of fresh water by 64.38 %. This reduction in the DM as well as fresh water has reduced the load of waste water to 27.94 %.

Table 6.10 Benefits of water pinch technology (Problem 3.3)

	Before Analysis	After Analysis	Net Savings(tph)
DM Water	337	223	114
Concentration of solids (ppm)	244	369	-

6.4.2 Cost Analysis

The basis of costing is very important for carrying out cost analysis. **Table 6.11** presents the power comparison of different modified water network with existing water network. **Table 6.12** shows the cost of different modified water networks such *reuse, regeneration-reuse* and *regeneration-recycling* along with existing water network. It has been prepared by considering various data presented as shown in Appendix B. **Table 6.12** represents the comparison of cost of water networks based on changes in flow rate of DM water, changes in pipe sizes and thus necessary cost associated with piping layout (i.e. civil, structural, erection and commissioning cost).

Table: 6.11 Power consumption comparison of different modified water network with existing water network

Specifications	*DM water (Existing)*	*DM water Network (reuse)*
Pump Capacity (delivered) (m^3/ h)	340	224
Pump Head (delivered) (m)	30	30
Efficiency of pump (%)	65	65
Power consumption (kW)	42.75	28.2
Motor efficiency (%)	90	90
Current drawn at full capacity (A)	120	80
Power consumption (kW)	47.5	32
No. of unit per hour (kW-h)	47.5	32
Cost of power (INR / unit)	4	4
Total cost of power consumption (INR per hour)	190	128
Operating hours	24	24
No. of operating days	365	365
Total cost of power consumption per year	16,64,400	11,21,280
Total Savings in Power consumption per year	5,43,120	

Table 6.12 Cost comparison of different modified network with exiting network

Total Cost of network	*DM water (Existing)*	*DM water Network (reuse)*
Fixed cost of centrifugal pump	95,000	75,000
Fixed cost of electric motor	55,000	35,000
Fixed cost of Base plate + accessories +Civil foundation of centrifugal pump	7,500	20,000
Fixed cost of piping layout from DM water storage tank to plant storage tank	36,750	1,715
Fixed cost of accessories for piping layout	3,675	25,725
Break up of erection and commissioning cost of piping layout		
(1) Cost of civil work	3,675	2,573
(2) Cost of welding work	2,940	2,058
(3) Cost of piping layout work	5,513	3,859
(4) Support Structure for pipeline layout work	919	643
Total cost of electrical panel, cables etc.	95,000	65,000
Total cost of piping layout from Operation 1 to other units as per existing and modified networks	29,106	29,106
Total cost of piping layout from Operation 2 to other units as per existing and modified networks	64,680	80,850
Total cost of piping layout from Operation 3 to other units as per existing and modified networks	72,765	72,765
Total cost of piping layout from Operation 4 to other units as per existing and modified networks	51,744	87,318
Total cost of piping layout from Operation 5 to other units as per existing and modified networks	29,106	97,020
Total cost of piping layout from Operation 6 to other units as per existing and modified networks	19,404	29,106
Total cost of piping layout from Operation 7 to other units as per existing and modified networks	19,404	19,404
Total cost of piping layout from Operation 8 to other units as per existing and modified networks	38,808	25,872
Total cost of piping layout from Operation 9 to other units as per existing and modified networks	48,510	48,510
Total cost of piping layout from Operation 10 to other units as per existing and modified networks	38,808	71,148
Fixed cost of discharge header from plant to ETP sump	57,000	47,500
Fixed cost of valves	29,000	28,000
Fixed cost of instrumentation	3,95,000	3,60,000
Total Cost of network (INR)	***11,99,306***	***12,28,171***

6.5 Salient results of cost analysis OF PROBLEM 3.4

6.5.1 Benefit Analysis

Table 6.13 represents the benefit of water pinch technology. It compares modified water using networks with that of existing ones for present case study. It also represents the net savings in water consumption and load on effluent treatment plant based on the modifications. It can be observed that the water-pinch analysis reduced the consumption of DM water as well as fresh water to a considerable extent. For the above case study the flow rate of DM water is reduced by 28% and that of fresh water by 64.38 %. This reduction in the DM as well as fresh water has reduced the load of waste water to 27.94 %.

Table 6.13 Benefits of water pinch technology (Problem 3.4)

	Before Analysis	After Analysis	Net Savings(tph)
DM Water	50	36.00	14
Fresh Water	100	35.62	64.38

6.5.2 Cost Analysis

Table 6.14 presents the power comparison of different modified water network with existing water network. **Table 6.15** shows the cost of different modified water networks such *reuse, regeneration-reuse* and *regeneration-recycling* along with existing water network. It has been prepared by considering various data presented as shown in Appendix B. **Table 6.15** represents the comparison of cost of water networks based on changes in flow rate of DM water, changes in pipe sizes and thus necessary cost associated with piping layout (i.e. civil, structural, erection and commissioning cost).

Table: 6.14 Power consumption comparison of different modified water network with existing water network

Specifications	*DM water (Existing)*	*Fresh water Network (Existing)*	*DM water Network (reuse)*	*Fresh water network (reuse)*
Pump Capacity (delivered) (m^3/ h)	51	100	36	31
Pump Head (delivered) (m)	30	30	30	30
Efficiency of pump (%)	65	65	65	65
Power consumption (kW)	6.29	12.57	4.52	3.9
Motor efficiency (%)	90	90	90	90
Current drawn at full capacity (A)	17.64	35.27	12.68	10.94
Power consumption (kW)	6.98	13.96	5.02	4.33
No. of unit per hour (kW-h)	6.98	13.96	5.02	4.33
Cost of power (INR / unit)	4	4	4	4
Total cost of power consumption (INR per hour)	27.92	55.84	20.09	17.32
Operating hours	24	24	24	24
No. of operating days	365	365	365	365
Total cost of power consumption per year	2,44,579	4,89,158	1,75,988	1,51,723
Total Savings in Power consumption per year (Combining DM and Fresh Water Network) (INR per year)			4,06,026	

Table 6.15 Cost comparison of different modified network with exiting network

Total Cost of network	*DM water (Existing)*	*Fresh water Network (Existing)*	*DM water Network (reuse)*	*Fresh water network (reuse)*
Fixed cost of centrifugal pump	35,000	40,000	25,000	15,000
Fixed cost of electric motor	10,000	12,000	7,000	7,000
Fixed cost of Base plate + accessories +Civil foundation of centrifugal pump	5,000	5,000	2,500	1,500
Fixed cost of piping layout from DM water storage tank to plant storage tank	24,500	1,470	24,500	29,400
Fixed cost of accessories for piping layout	2,450	44,100	2,450	2,940
Break up of erection and commissioning cost of piping layout				
(1) Cost of civil work	2,450	4,410	2,450	2,940
(2) Cost of welding	1,960	3,528	1,960	2,352

(3) Cost of piping layout	3,675	6,615	3,675	4,410
(4) Support Structure for pipeline layout	6,12.5	1,103	613	735
Total cost of electrical panel, cables etc.	10,500	18,250	6,500	11,000
Total cost of piping layout from Reactor 1 to other units as per existing and modified networks	24,255	32,340	65,489	16,170
Total cost of piping layout from Separators to other units as per existing and modified networks	24,255	16,979	78,425	39,617
Total cost of piping layout from Grinding Mill to other units as per existing and modified networks	25,872	24,255	57,404	16,170
Total cost of piping layout from Washing Section to other units as per existing and modified networks	16,170	16,979	42,851	8,085
Fixed cost of discharge header from plant to ETP sump	28,500	49,400	0	65,170
Fixed cost of valves	9,600	11,500	9,600	8,100
Fixed cost of instrumentation	1,37,500	1,41,500	1,37,500	1,25,500
Total Cost of network (INR)	***3,62,300***	***4,29,428***	***4,67,915***	***3,56,089***

6.6 Salient results of cost analysis OF PROBLEM 3.5

Table 6.16 presents the annual cost benefit analysis due to reduction in power and water consumption for different proposals.

Table 6.16 Cost benefit analysis due to reduction in fresh water and power consumption for different proposals

Proposal	Fresh water flow rate to be supplied from overhead storage tank (tph)	Make up water requirement (tph)	Savings in fresh water (tph)	Saving in Make up water cost (Make up water : 50 % RO water + 50 % fresh water) (A)	Savings in current drawn by different drives (A)	Savings Unit per Hour (kWh)	Savings Unit per Day	Savings in unit per season	Total savings per year in cost of power consumption (Rs) (B)	Total Savings per season (A + B)
Summer Season (210 days operation)										
Existing	**1296**	**10**	--	--						
Proposal 1A	770.4	6.5	525.6	1,36,710	116	46	1104	2,31,840	9,27,360	10,64,070
Proposal 2A	968.2	7.85	327.8	83,979	38.5	15	360	75,600	3.02.400	3,86,379
Proposal 2A Special Case 1	712.2	5.7	583.8	1,67,958	123.9	49	1176	2,46,960	9,87,840	**11,55,798**
Proposal 2A Special Case 2	380.2	3.0	915.8	2,73,420	87	35	840	1,76,400	7,05,600	9,79,020
Winter Season (155 days operation)										
Existing	**1296**	**10**	--	--						
Proposal 2B	968.2	7.85	327.8	61,985	208	83	1992	3,08,760	12,35,040	12,97,025
Proposal 2B Special Case 2	588	4.7	708	1,52,799	38.5	15	360	55,800	2,23,200	3,75,999
Proposal 2B Special Case 1	488	3.9	808	1,75,863	159	63	1512	2,34,360	9,37,440	11,13,303
Proposal 1B	526.8	4.21	769.2	1,66,926	211	84	2016	3,12,480	12,49,920	**14,16,846**

CHAPTER 7

SUMMARY REPORTS FOR ALL PROBLEM STATEMENTS

7.1 Result Summary for Problem 3.1

Problem 3.1 → Analyze system *without any reuse*

Existing Flow rate of DM water: 50 tph
Existing cost of water network: 3,78,265 INR
Existing cost of power consumption: 2,64,902 INR per year
Existing cost of DM water: 43,80,000 INR per year

Analyze system with ***reuse***

Modified Flow rate of DM water: 31.9 tph
Modified cost of water network: 3,77,318 INR
Modified cost of power consumption: 1, 56,628 INR per year
Modified cost of DM water: 26,54,718 INR per year

Savings due to reduce DM water requirement: ***17,25,282 INR per year***

Savings due to reduce power consumption: ***1,08,274 INR per year***

Analyze system with ***regeneration-reuse***

Modified Flow rate of DM water: 21.6 tph
Modified cost of water network: 11,31,207 INR
Modified cost of power consumption: 1, 05,470 INR per year
Modified cost of DM water: 17,97,552 INR per year

Savings due to reduce DM water requirement: ***25,82,448 INR per year***

Savings due to reduce power consumption: ***2,72,795 INR per year***

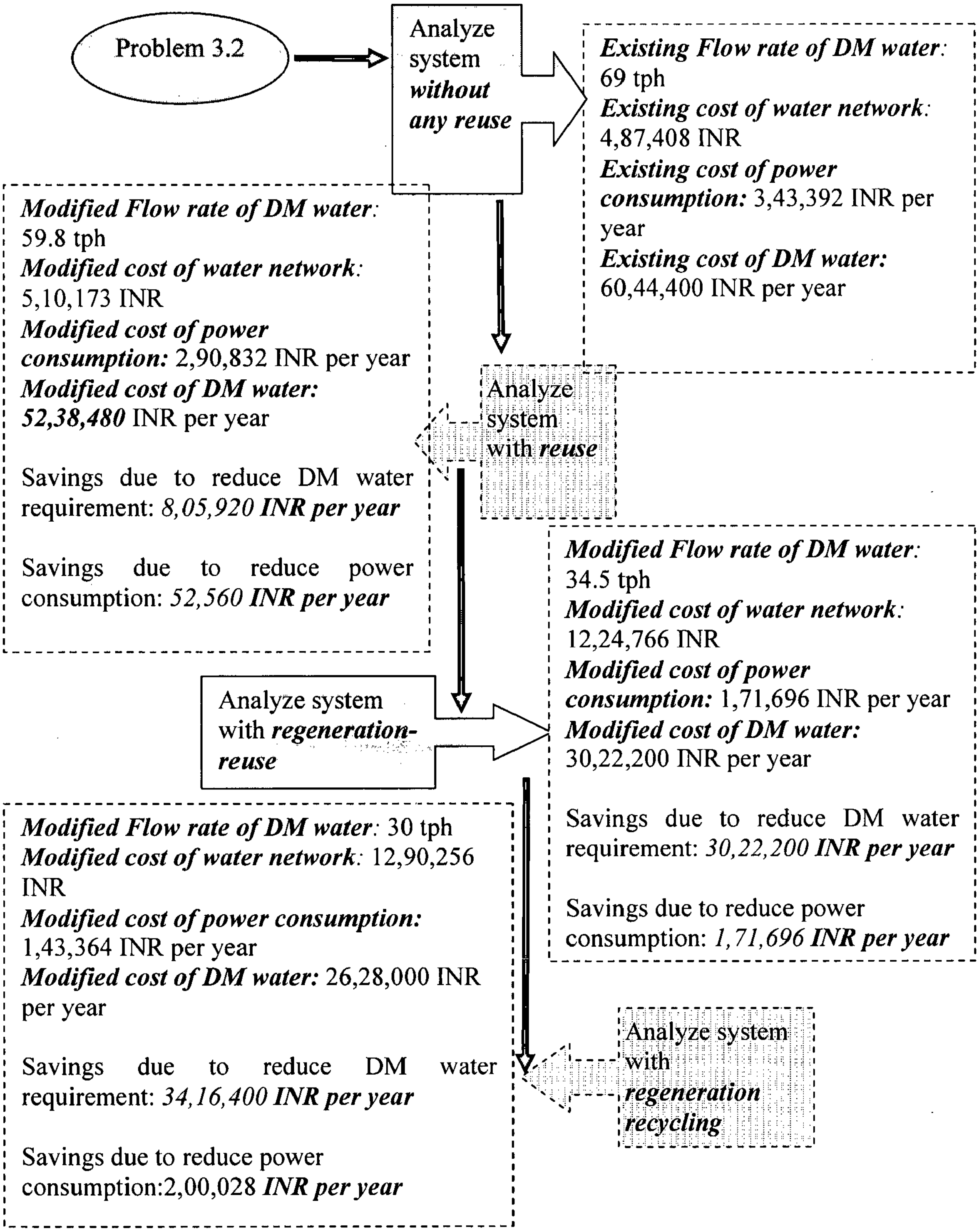
Analyze system with ***regeneration recycling***

Modified Flow rate of DM water: 12 tph
Modified cost of water network: 12,32,775 INR
Modified cost of power consumption: 58,867 INR per year
Modified cost of DM water: 9,98,640 INR per year

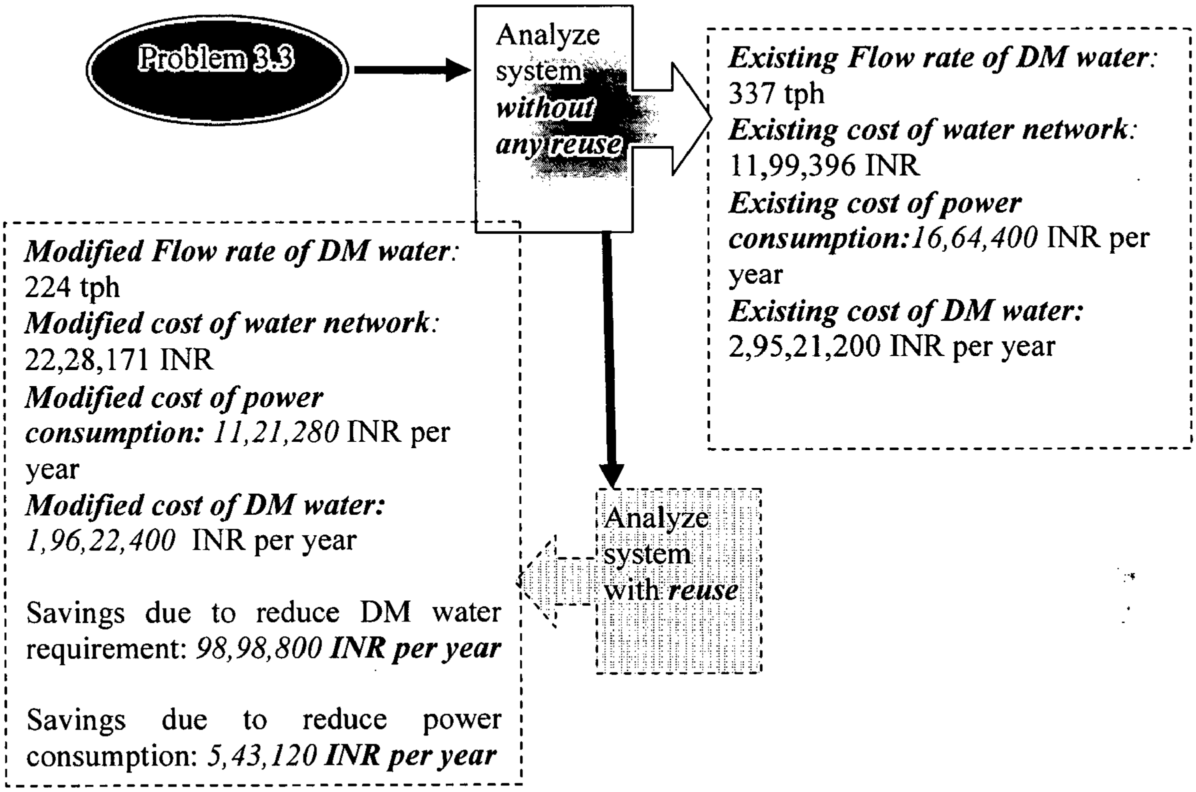
Savings due to reduce DM water requirement: ***33,81,360 INR per year***

Savings due to reduce power consumption: ***2,06,035 INR per year***

7.2 Result Summary for Problem 3.2



7.3 Result Summary for Problem 3.3



7.4 Result Summary for Problem 3.4

Problem 3.4 → Analyze system ***without any reuse***

Existing Flow rate of DM water: 51 tph
Existing Flow rate of fresh water: 100 tph

Existing cost of DM water network: 3,62,300 INR

Existing cost of Fresh water network: 4,29,428 INR

Existing cost of power consumption (DM water network) :2,44,579 INR per year

Existing cost of DM water: ***44,67,600*** INR per year

Existing cost of power consumption (fresh water network) :4,89,158 INR per year

Existing cost of fresh water: ***30,66,000*** INR per year

Analyze system with ***reuse***

Modified Flow rate of DM water: 36 tph
Modified Flow rate of fresh water: 35.6 tph

Modified cost of DM water network: 4,67,915 INR

Modified cost of Fresh water network: 3,56,089 INR

Modified cost of power consumption (DM water network) : 1,75,988 INR per year

Modified cost of DM water: ***31,53,600*** INR per year

Modified cost of power consumption (fresh water network) : 1,51,723 INR per year

Modified cost of fresh water: ***10,91,496*** INR per year

Savings due to reduce DM water requirement: *13,14,000 INR per year*
Savings due to reduce fresh water requirement: *19,74,504 INR per year*

Savings due to reduce power consumption: *4,06,026 INR per year*

Proposal	Fresh water flow rate to be supplied from overhead storage tank (tph)	Make up water requirement (tph)	Savings in fresh water (tph)	Saving in Make up water cost (Make up water : 50 % RO water + 50 % fresh water) (A)	Savings in current drawn by different drives (A)	Savings Unit per Hour (kWh)	Savings Unit per Day	Savings in unit per season	Total savings per year in cost of power consumption (Rs) (B)	Total Savings per season (A + B)
Summer Season (210 days operation)										
Existing	**1296**	**10**	--	--						
Proposal 1A	770.4	6.5	525.6	1,36,710	116	46	1104	2,31,840	9,27,360	10,64,070
Proposal 2A	968.2	7.85	327.8	83,979	38.5	15	360	75,600	3.02.400	3,86,379
Proposal 2A Special Case 1	712.2	5.7	583.8	1,67,958	123.9	49	1176	2,46,960	9,87,840	**11,55,798**
Proposal 2A Special Case 2	380.2	3.0	915.8	2,73,420	87	35	840	1,76,400	7,05,600	9,79,020
Winter Season (155 days operation)										
Existing	**1296**	**10**	--	--						
Proposal 2B	968.2	7.85	327.8	61,985	208	83	1992	3,08,760	12,35,040	12,97,025
Proposal 2B Special Case 2	588	4.7	708	1,52,799	38.5	15	360	55,800	2,23,200	3,75,999
Proposal 2B Special Case 1	488	3.9	808	1,75,863	159	63	1512	2,34,360	9,37,440	11,13,303
Proposal 1B	526.8	4.21	769.2	1,66,926	211	84	2016	3,12,480	12,49,920	**14,16,846**

7.5 Result Summary for Problem 3.5

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

The Guide to Conducting a Water Pinch Analysis Investigation presented in Chapter 4 of the report attempts to summarize the experience gained during these investigations, and is perhaps the chief immediate outcome of this dissertation.

Industrial awareness of the technique in India has been raised through direct interaction with industries involved in the case studies and through conference papers, Workshops and courses presented during the project, however there is a way to go before water pinch analysis can be considered as an accepted and establish practice.

8.1 Conclusions

The following main conclusions can be drawn based on different industrial case studies about the significance of water pinch analysis:

- For the first problem, the DM water consumption is 50 tph before modification and after modification using water pinch it reduces to 31.9 tph *(reuse)*, 21.6 tph (*regeneration-reuse*) and 12 tph (*regeneration-recycling*). The results obtained from the present analysis are compared well with the results obtained from well established software ASPEN WATER. The cost benefit analysis illustrates that the profit obtained in the case of reuse is 22,01,914 INR per year and the pay back period for the *regeneration-reuse* and *regeneration –recycling* are 2.5 and 2.3 month.
- The second problem is viewed as a single contaminant problem and the DM water consumption is 69 tph before modification and after modification using water pinch it reduces to 59.8 tph *(reuse)*, 34.5 tph (*regeneration-reuse*) and 30 tph (*regeneration-recycling*). The cost benefit analysis illustrates that the profit obtained in the case of reuse is 17,63,914 INR per year and the pay back period for the *regeneration-reuse* and *regeneration –recycling* are 1.8 and 1.1 month.
- For the third problem, which involves ten operations and only approach of water *reuse* been applied. The DM water consumption is 337 tph before modification and after modification using water pinch it reduces to 221.5 tph

(reuse). The cost benefit analysis illustrates that the profit obtained in the case of reuse is 5,43,120 INR per year.

- ➢ The fourth problem was identified as a multi contaminant, *reuse* problem. The fresh water consumption and DM water consumption are 100 tph and 51 tph respectively before modification and the network is dealing with three major contaminant such as total organic content (TOC), total dissolved solids (TDS) and total suspended solids (TSS). The improved water using network designed for the present work consumed less DM & fresh water. The reductions are of the tune of 28% and 64.38 % for DM and fresh water respectively. Due to alteration in piping, there will be a saving of 4,06,026 INR per year, which will be utilized for development of efficient environment policy for the company.
- ➢ The concept of water-pinch couple coupled with thermal analysis is applied on cooling water networks of different sections, namely, furnace melting, neck-refining & spout and tin bath, of a Glass industry of India commissioned in the year 2006. The analysis takes in to account mixing of multiple intermediate cooling water streams to satisfy the constraints of the network. Different proposal had been worked out and different strategies had been proposed for summer and winter season. The results are very encouraging and there will be huge benefit in terms of power and fresh water consumption, if the proposed modified networks have been put into real operations. There will be a savings in fresh water, make up water and power consumptions. The maximum projected savings will be of 11,55,978 INR for summer season and 14,16,846 INR for winter season operations.

Apart from above case studies, following general conclusions are :

- A water pinch analysis provides a clear and systematic picture of the water requirements of a system of processes, subject to the constraints imposed by the technology of the processes and the environment in which they operate.
- By identifying the factors which limit further reduction in the water requirements, the technique can focus attention on those areas of the process where technologicalimprovements will be most beneficial in improving water efficiency.

- By quantifying the impacts of technological and regulatory limits on a process, water pinch analysis has the potential to provide a rational tool for negotiation between an industry, water authorities and other role players.
- Because India is a water-scarce country, many India industries have responded to pressure to conserve water, and already have processes which use water relatively efficiently when compared to many industrialized countries. This means that dramatic savings in water use, as sometimes claimed in the international literature, are often not as readily available in India.
- There is a need for a scoping technique to provide a rapid assessment of a process to estimate the scope that it offers for improvement as a result of conducting a water pinch analysis.
- Gathering the necessary data on a system is almost always the most difficult and most time-consuming step in a water pinch analysis. It is unlikely that all the required data will be obtained at the first attempt, and so an iterative process which alternates between data gathering and analysis occurs.
- It is difficult, if not impossible, for an effective pinch investigation to be undertaken by a consultant outside the industrial organization concerned, unless it is done with the full commitment and participation of the organization at all stages.

8.2 Recommendations

1) Further efforts are required to encourage wider acceptance of water pinch analysis by Indian industry. This should be undertaken in conjunction with industry on a case study basis.
2) Further work is needed to extend the water pinch analysis methodology to account for chemically reacting solutes and aqueous reagents.
3) Techniques for the early identification of the applicability of water pinch need to be developed, rather than solving it as a retrofitting case.
4) Techniques need to be developed to reduce the time and effort required to gather the data needed for a water pinch analysis.
5) More explorations should be devoted to mathematical programming approach to obtain optimize results.

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APPENDIX A

EXISTING WATER NETWORKS FOR PROBLEM STATEMENTS

A.1

Existing Water Network

Fig A.1 represents the schematic diagram of the water consuming units such as filter washing machine (FWM), Doroclones (D), Screens (SCR) and Grinder (GR) of a typical Chemical Industry producing starch.

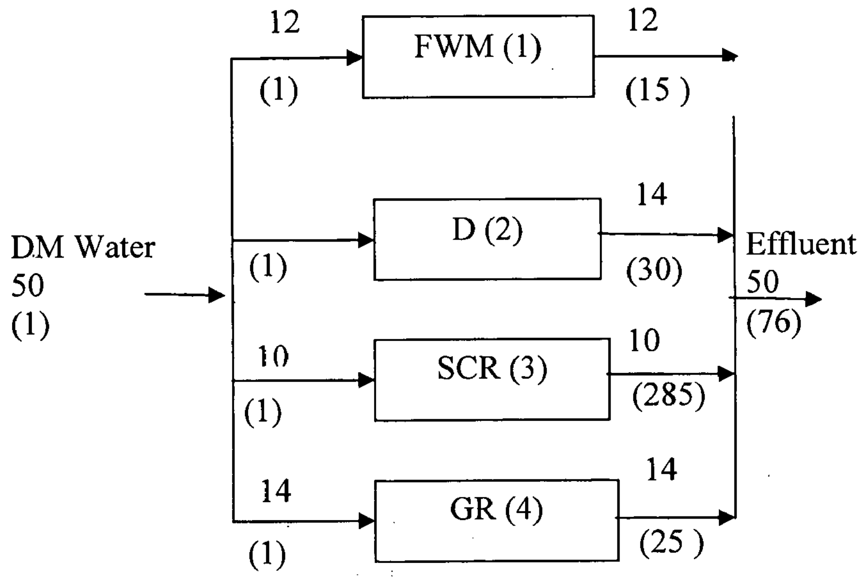

Fig.A.1 Existing water network for Problem 3.1

Note: *Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.*

A.2

Existing Water Network

A water using network has been selected from Starch industry situated in the state of Gujarat of India. The original network is shown in **Fig.A.2.** It represents the schematic diagram of the water consuming units such as primary separators (PS-I & PS-II), reactor (R), washing screens (DW) and fiber separators (S).

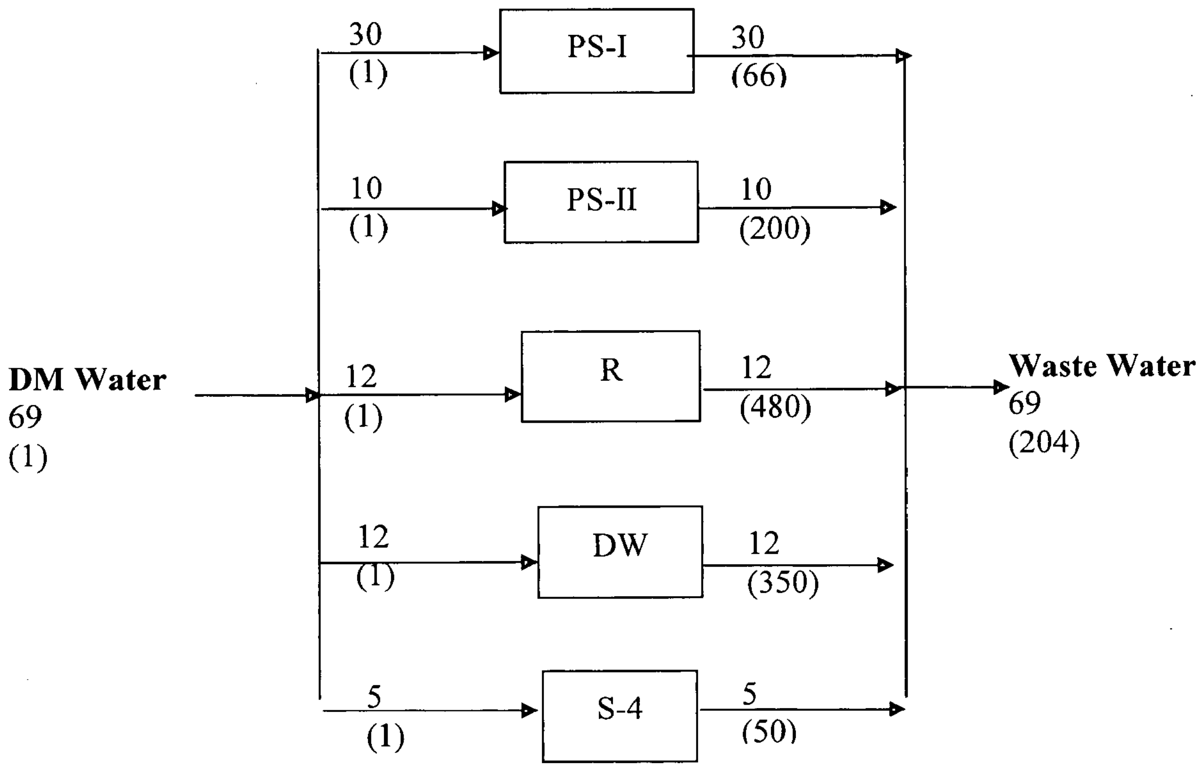

Fig.A.2 Existing water network for Problem 3.2

Note: *Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.*

A.3

Existing Water Network

A water using network has been selected from glucose section of a starch industry situated in the state of Gujarat of India. The original network is shown in **Fig.A.3.** It represents the distribution of DM water through different operations.

A.4

Existing Water Network

In the present study a water using network has been selected from Starch industry situated in the state of Gujarat of India. The original network is shown in **Fig.A.4.** The fresh water consumption and DM water consumption are 100 tph and 51 tph respectively. Due to process constraints, it has been found that it is not feasible to reuse water from any other water using operations to Reactor (R-1) & Separators (S). There are constraints related to concentration of contaminants for each unit.

A.5

Existing Water Network

Industrial process water system of a nearby glass industry with different water using processes is shown schematically in **Fig.A.5.1 and A.5.2.**

Note: Values shown without brackets are flow rates of DM water in tph where as value within small brackets are concentration of contaminants in ppm.

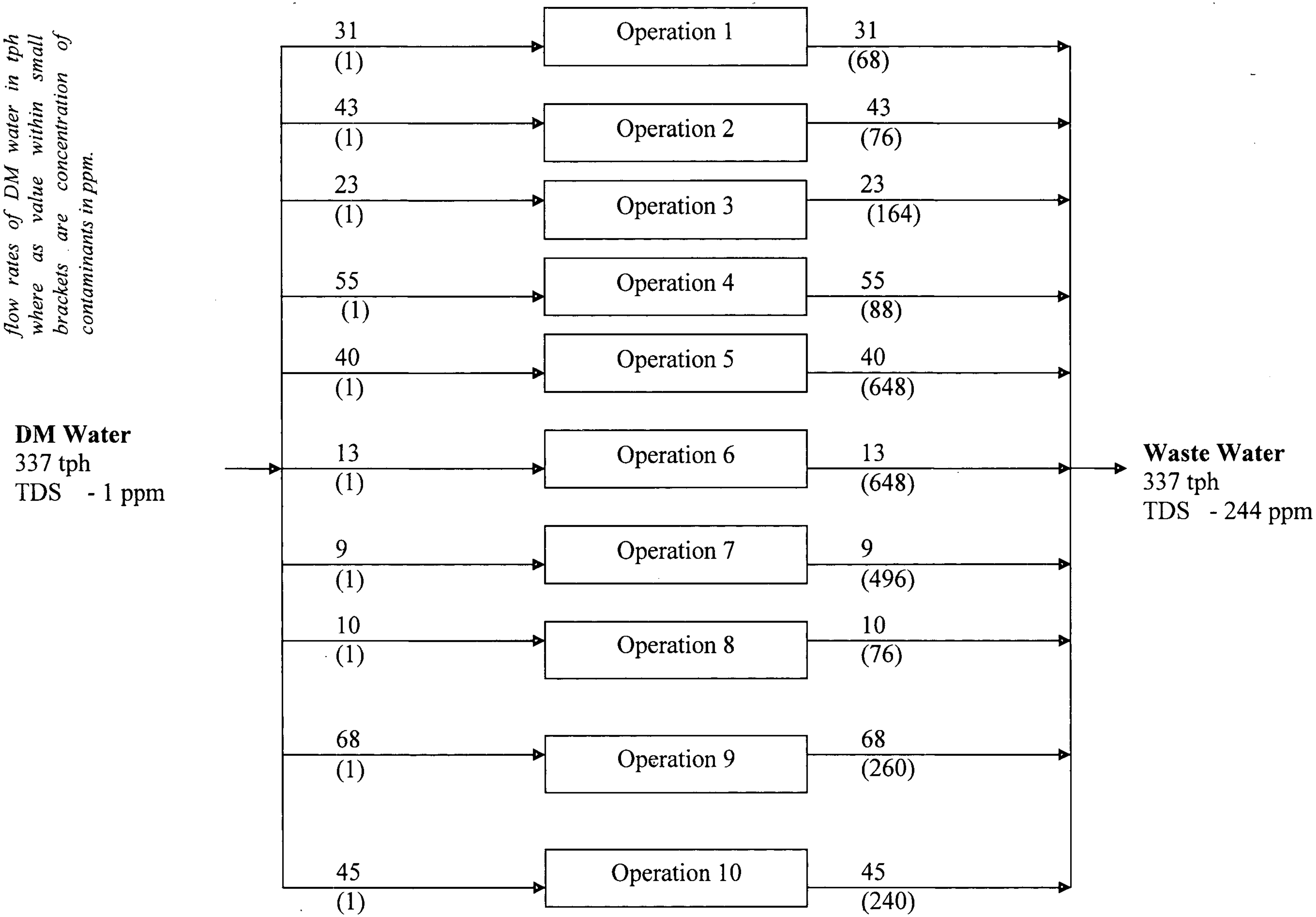

Fig A 3 Existing water network for Problem 3 3

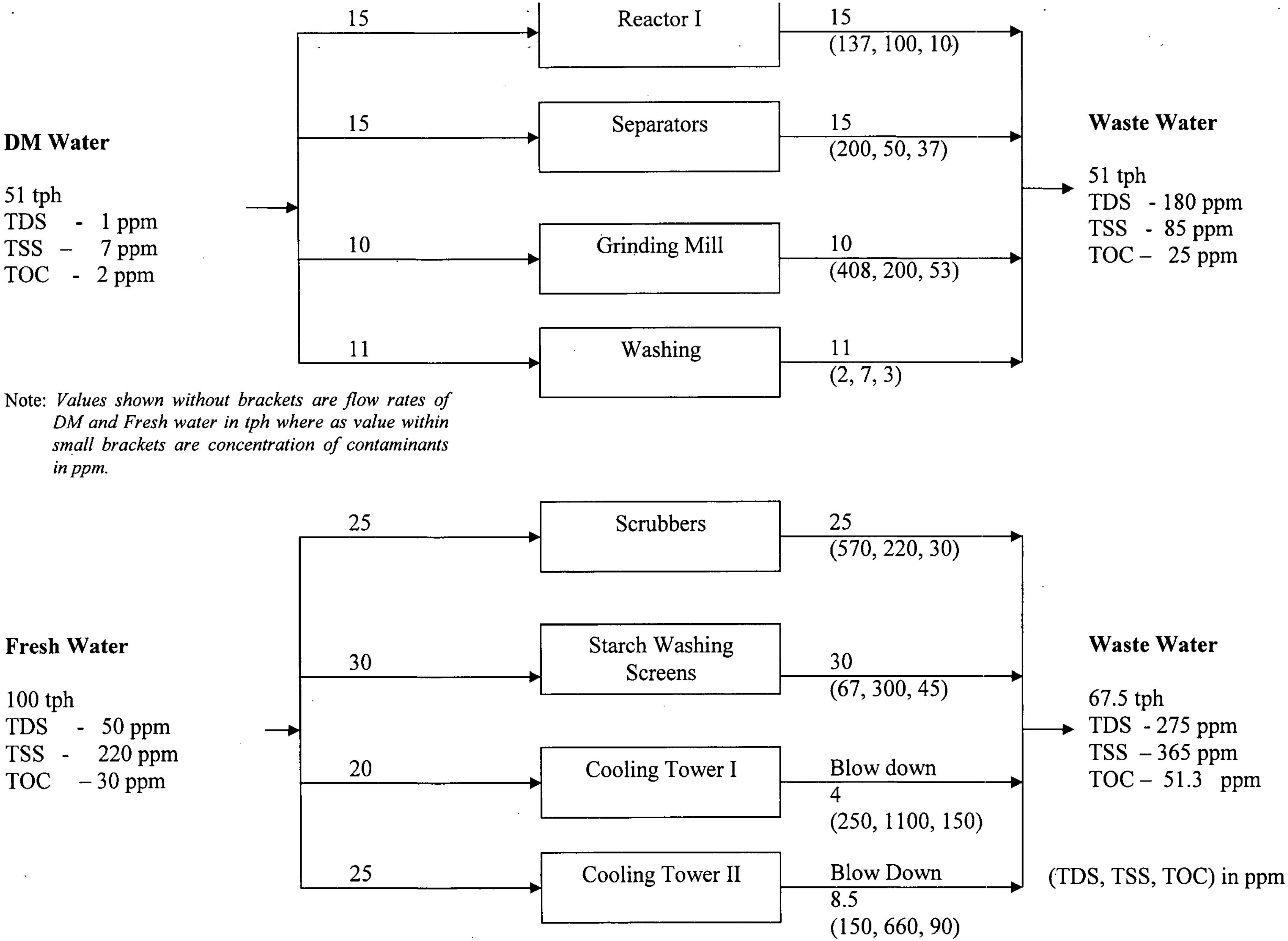

Fig A 4 Existing water network for Problem 3.4

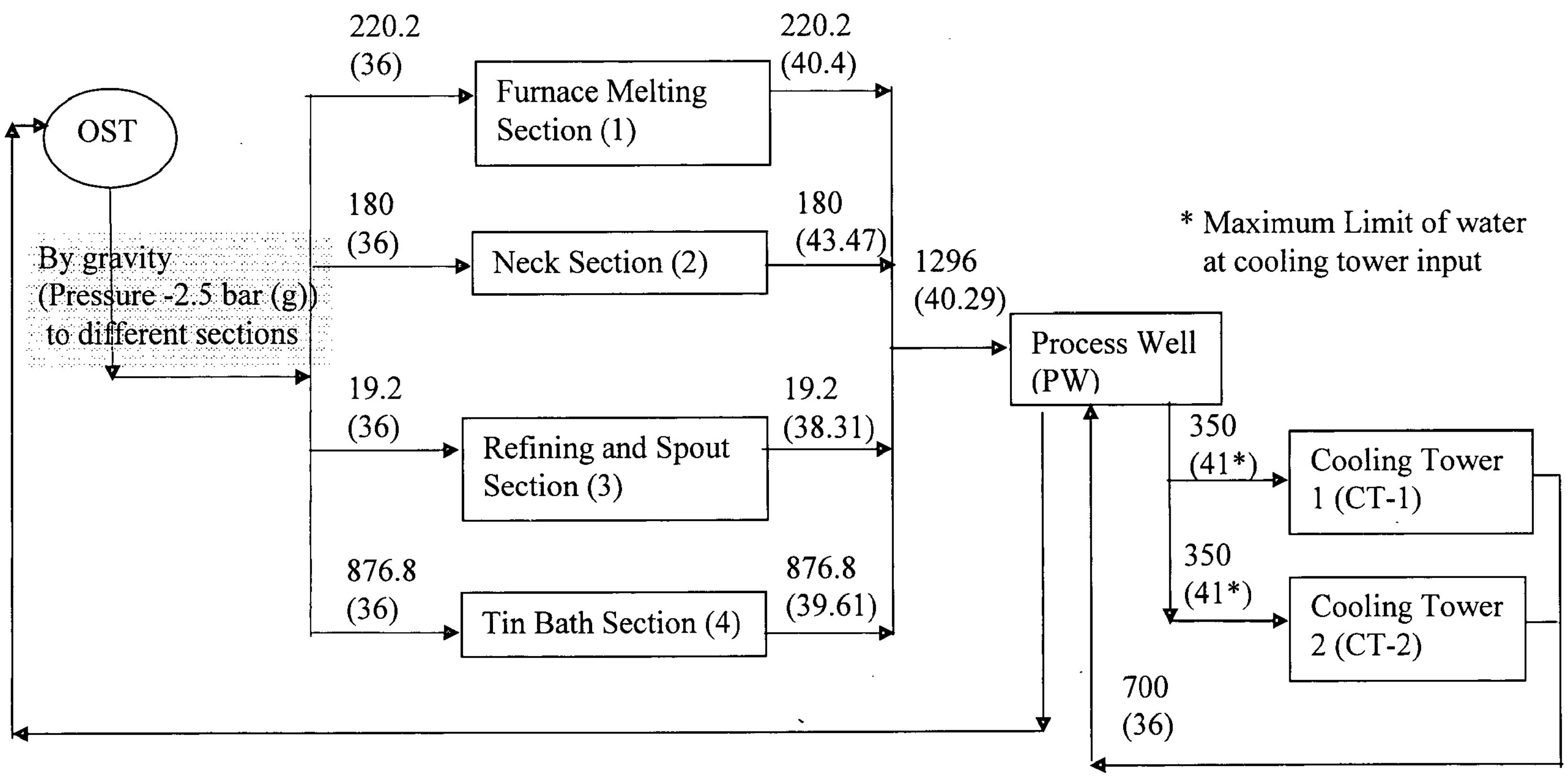

Fig. A.5.1 Existing Water Network (Summer Season) for Problem 3.5

Note: *Values shown without brackets are flow rates of cooing water in tph where as value within small brackets are temperature in (^0C)*

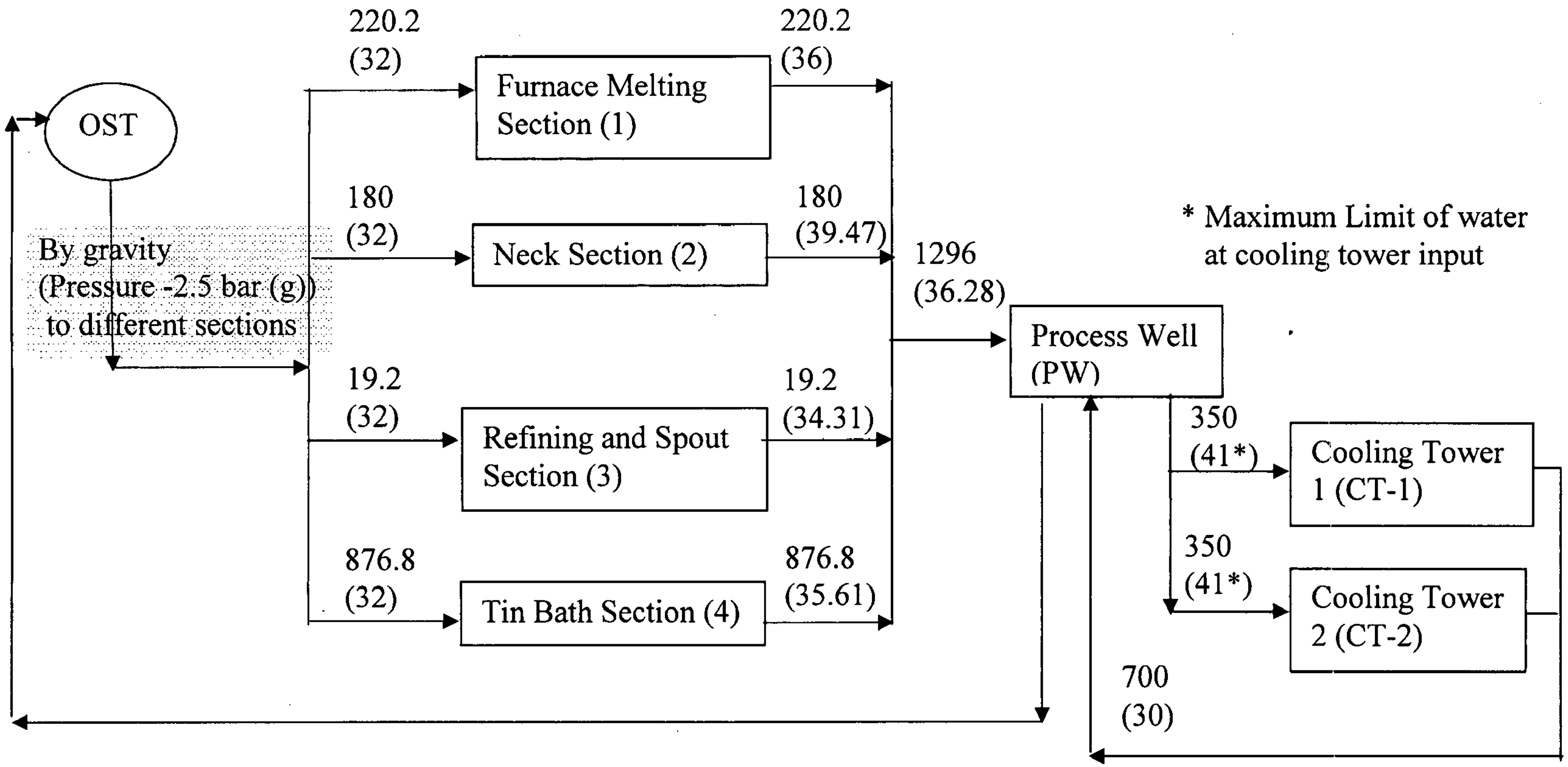

Fig. A.5.2 Existing Water Network (Winter Season) for Problem 3.5

Note: *Values shown without brackets are flow rates of cooing water in tph where as value within small brackets are temperature in* (^{0}C)

APPENDIX B

IMPORTANT DATA FOR COST ESTIMATION FOR PROBLEM STATEMENTS

Problem 3.1

Table B.3.1.1 Detail piping layout of existing water network

Piping layout from one operation to another	Pipe Length (m)
From DM water storage tank to plant storage tank	100
From plant storage tank to FWM	30
From plant storage tank to D	50
From plant storage tank to SCR	75
From plant storage tank to GR	40

Table B.3.1.2 Details of pump and power consumption of existing water network

Specifications	Value
Pump Capacity (Delivered)	50 m^3/ h
Pump Head (Delivered)	30 m
Efficiency of pump	60 %
Power Consumption	6.81 kW
Motor Efficiency	90 %
Current drawn at full capacity	19.1 A
Distance from main panel to motor	100 m

Table B. 3.1.3 Distance from new proposed regeneration unit to existing units

Distance from new proposed regeneration unit (REG) to existing unit	Distance (m)
REG-1 to S	20
REG-1 to SCR	50
REG-1 to GR	25
SCR to REG-2	50

Problem 3.2

Table B.3.2.1 Detail piping layout of existing water network

Piping layout from one operation to another	Pipe Length (m)
From DM water storage tank to plant storage tank	100
From plant storage tank to PS-I	30
From plant storage tank to PS-II	50
From plant storage tank to R	75
From plant storage tank to DW	40
From plant storage tank to S-4	40

Table B.3.2.2 Details of pump and power consumption of existing water network

Specifications	**Value**
Pump Capacity (Delivered)	50 m^3/ h
Pump Head (Delivered)	30 m
Efficiency of pump	60 %
Power Consumption	6.81 kw
Motor Efficiency	90 %
Current drawn at full capacity	19.1 A
Distance from main panel to motor	100 m

Table B.3.2.3: Distance from new proposed regeneration unit to existing units

Distance from new proposed regeneration unit (REG) to existing unit	Distance (m)
REG-1 to R	75
REG-1 to DW	50
REG-1 to PS II	35
REG-1 to PS I	50
REG-1 to S-4	35

Problem 3.3

Table B.3.3.1 Detail piping layout of existing water network

Piping layout from one operation to another	Pipe Length (m)
From DM water storage tank to plant storage tank	25
From plant storage tank to Operation 1	30
From plant storage tank to Operation 2	50
From plant storage tank to Operation 3	75
From plant storage tank to Operation 4	40
From plant storage tank to Operation 5	30
From plant storage tank to Operation 6	30
From plant storage tank to Operation 7	30
From plant storage tank to Operation 8	40
From plant storage tank to Operation 9	30
From plant storage tank to Operation 10	30

Table B.3.3.2 Details of pump and power consumption of existing water network

Specifications	**Value**
Pump Capacity (Delivered)	340 m^3/ h
Pump Head (Delivered)	30 m
Efficiency of pump	65 %
Power Consumption	42.75 kW
Motor Efficiency	90 %
Current drawn at full capacity	120 A
Distance from main panel to motor	100 m

Table3.3.3: Distance between existing units

Distance between existing units.	**Distance (m)**
between operation 1 to operation 2	50
between operation 1 to operation 5	70
between operation 1 to operation 5	70
between operation 2 to operation 4	50
between operation 3 to operation 4	35

Problem 3.4

Table B.3.4.1 Detail piping layout of existing water network

Piping layout from one operation to another	Pipe Length (m)
From DM water storage tank to plant storage tank	25
From plant storage tank to R-1	25
From plant storage tank to S	25
From plant storage tank to G	40
From plant storage tank to W	25
From Fresh water storage tank to plant storage tank	30
From plant storage tank to SCR	50
From plant storage tank to SWS	35
From plant storage tank to CT1	50
From plant storage tank to CT2	35

Table B.3.4.2 Details of pump and power consumption of existing water network

Specifications	**Fresh water transfer pump**	**DM water Transfer pump**
Pump Capacity (Delivered)	100 m^3/ h	51 m^3/ h
Pump Head (Delivered)	30 m	30 m
Efficiency of pump	65 %	65 %
Power Consumption	12.57 kW	6.29 kW
Motor Efficiency	90 %	90 %
Current drawn at full capacity	36 A	18 A
Distance from main panel to motor	50 m	50 m
Total Qty of pressure gauge	1 No	1 No

Table B.3.4.3 Distance from new proposed regeneration unit to existing units

Distance between equipments	m	Distance between equipments	m
R-1 to SCR	25	S to CT-2	85
R1- to SWS	30	G to SCR	65
R-1 to CT-1	50	W to G	25
R-1 to CT-2	60	CT-1 to SWS	45
S to SCR	35	CT2 to CT1	25
S to SWS	45		

Problem 3.5

Table B.3.5.1 Cost of Power and Make up water

Specification	Cost
Cost of Power	Rs 4 / kW
Cost of Fresh water	Rs 3.5 / m^3
Cost of RO water	Rs 12 / m^3
Existing Qty of make up water	10 m^3 /h

Table B.1 Piping cost per unit m length for different sizes

Specifications (ASTM A312 TP 304)	Cost (INR / unit length)
Cost of pipe (0.3 m)	2940 INR / m
Cost of pipe (0.25 m)	2450INR / m
Cost of pipe (0.2 m)	1960 INR / m
Cost of pipe (0.175 m)	1715 INR / m
Cost of pipe (0.15 m)	1470 INR / m
Cost of pipe (0.125 m)	1225 INR /m
Cost of pipe (0.1 m)	980 INR /m
Cost of pipe (0.075 m)	735 INR /m
Cost of pipe (0.050 m)	490 INR /m
Cost of pipe (0.050 m)	245 INR /m

Table B.2 Accessories cost and erection and commissioning cost of piping layout for different modified networks

Total Cost of Accessories (Bend, Flange, Gaskets, Bolts-Nuts, Round Neck)	10 % of total piping cost
Erection cost of pipeline	
(1) Civil Cost	10 % of total piping cost
(2) Welding Cost	8 % of total piping cost
(3) Pipeline laying cost	15 % of total piping cost
(4) Support Structure of pipeline	2.5 % of total piping cost

APPENDIX C

COMPUTER PROGRAM and MICROSOFT EXCEL SHEETS

The computer programs to determine the minimum fresh water flow rates based on the limiting concentration composite curve method, proposed by Wang and Smith was developed in the MATLAB programming. Two programs were developed. These programs are described below in Table C.1.

Table C.1. The details of the computer programs

Sr.No.	Name of Programs	Purpose of the programs
1	Program C.MB	This program gives the values of the limiting fresh water flow rates. It takes the help of different input files to solve different problems (3.1 to 3.4)
2	CWCC.xls	This program calculate the construction of cold water composite curves for problem 3.5
3	TAC.xls	This program calculates the TAC and other profitability analysis for problem 3.1 to 3.4.

Program C1.MB :

Program to construct CID and generation of CCC

```
n=input('Enter the total number of streams');
Sl=input('Enter the sl. no of operation');
f=input('Enter the different flow` rates');
Cin=input('Enter the inlet concentration');
Cout=input('Enter the outlet concentration');
T=[Sl; f; Cin ;Cout];
fprintf('Input Data\n');
fprintf('----------\n');
fprintf(' Operation      fi(t/h)      Cin(ppm)    Cout(ppm)\n');
fprintf('-----------------------------------------------------------\n');
disp(T)
C=[Cin Cout];
a=2*N;
for i=1:a-1
for j=i+1:a
if C(i)= =C(j)
C(j)=0;
end
end
end
 Conc=nonzeros(C);
 Conc1=sort(Conc,'ascend');
 [m,n]=size(Conc1);
 p=m;
 Cj=zeros(m+1,n);
 for i=1:p
Cj(i+1)=Conc1(i);
 end
 fe=f';
 F=zeros(m+1,n);
for i=2:m+1
for j=1:N
if Cin(j)<=Cj(i-1)& Cout(j)>=Cj(i)
F(i)=F(i)+fe(j);
end
end
end
dC=zeros(m+1,n);
for i=2:m+1
dC(i)=Cj(i)-Cj(i-1);
```

```
end
 FI=F';
 dm=zeros(m+1,n);
for i=2:m+1
dm(i)=FI(i)*dC(i)*10^-3;
end
dM=cumsum(dm);
dM1=dM*1000;
CJ1=zeros(m+1,n);
CJ1=Cj-Cj(1);
FW=[];
 for i=2:m+1
FW(i)=dM1(i)/CJ1(i);
 end
FWs=FW';
F0=FI';
Soltable=[Cj F0 dm dM FWs];
fprintf('Mass Problem Table For Given Problem\n');
fprintf('---\n');
fprintf('   Cj(ppm)      fi(tph)      dmj(kg/h)      dmc(kg/h)      fws(tph)\n');
disp(Soltable);
A=max(FWs);
fprintf('The minimum water flow rate in t/h=%15f',A);
```

Table C.2 Cold composite curve for Problem 3.5

(Furnace melting , Neck and Refining –Spout Section)						Tin Bath Section					
Tin (^{0} C)	Tout (^{0} C)	Shifted Tin (^{0} C)	Shifted Tout (^{0} C)	Q (kW)	CP (kW /^{0} C)	Tin (^{0} C)	Tout (^{0} C)	Shifted Tin (^{0} C)	Shifted Tout (^{0} C)	Q (kW)	CP (kW /^{0} C)
36	43	36	43	781.38	111.626	36	38.5	36	38.5	87.2083	34.8833
36	44	36	44	781.38	97.6725	36	39.5	36	39.5	195.347	55.8133
36	37.5	36	37.5	6.27	4.18	36	37	36	37	0	0
36	38.5	36	38.5	24.41	9.764	36	40	36	40	0	0
36	38.5	36	38.5	20.93	8.372	36	37.5	36	37.5	6.279	4.186
36	41	36	41	586.04	117.208	36	40	36	40	781.387	195.347
36	39	36	39	83.72	27.9067	36	40	36	40	948.827	237.207
36	46	36	46	383.71	38.371	36	40	36	40	1004.64	251.16
36	37	36	37	6.97	6.97	36	40.5	36	40.5	376.74	83.72
36	37	36	37	6.97	6.97	36	39	36	39	125.58	41.86
36	37	36	37	11.16	11.16	36	37	36	37	1.39533	1.39533
36	37	36	37	19.53	19.53	36	37	36	37	1.39533	1.39533
36	37	36	37	8.372	8.372	36	37	36	37	1.39533	1.39533
36	37	36	37	19.53	19.53	36	37	36	37	1.39533	1.39533
T (^{0} C)	Q (kW)	Qcum (kW)				36	37	36	37	4.186	4.186
36		0				36	37	36	37	3.48833	3.48833
37	2740.37	2740.372				36	41	36	41	52.325	10.465
37.5	1333.92	4074.292				36	37	36	37	6.97667	6.97667
38.5	2661.57	6735.862				36	41	36	41	17.4417	3.48833
39	1308.12	8043.977				36	37	36	37	16.744	16.744
41	5065.02	13109				36	37.5	36	37.5	6.279	4.186
43	3892.94	17001.94				36	37	36	37	48.8367	48.8367

44	1165.09	18167.03				36	39	36	39	29.302	9.76733
46	767.42	18934.45				36	39	36	39	4.186	1.39533
						T (^{0} C)	Q (kW)	Qcum (kW)			
						36		0			
						37	1019.29	1019.291			
						37.5	466.739	1486.03			
						39	1387.66	2873.689			
						40	890.223	3763.912			
						40.5	418.6	4182.512			
						41	388.949	4571.461			

Table C.3 TAC Calculation (Problem 3.3)

TAC= Fixed cost / Service life + Operating cost per year

Service Life	10	Years			
BASE CASE			***Reuse***		
fixed cost	1199306		fixed cost	1228171	
fixed cost / service life	119931	Rs / year	fixed cost / service life	122817	Rs / year
operating cost per year			**operating cost per year**		
power cost per year	1664400	Rs / year	power cost per year	156629	Rs / year
Cost of DM Water	60	Rs / m^3	Cost of DM Water	48	Rs / m^3
Capacity of DM Water	340	m^3 / hr	Capacity of DM Water	223	m^3 / hr
Cost of DM water per Hour	20400	Rs / hr	Cost of DM water per Hour	10704	Rs / hr
Annual Operating Cost	178704000	Rs / year	Annual Operating Cost	93767040	Rs / year
Total annual opearing cost	180368400		Total annual operating cost	93923669	
TAC	**180488331**	**Rs / year**	**TAC**	**94046486**	**Rs / year**

able C.4 TAC Calculation (Problem 3.1)

AC= fixed cost / service life + operating cost per year

service life	10	years				
BASE CASE				***Reuse***		
fixed cost	378265			fixed cost	377318	
fixed cost / service life	37826	Rs / year		fixed cost / service life	37732	Rs / yea
operating cost per year				**operating cost per year**		
›wer cost per year	264902	Rs / year		power cost per year	156629	Rs / yea
ost of DM Water	11.5	Rs / m^3		Cost of DM Water	10.5	Rs / m^3
apacity of DM Water	50	m^3 / hr		Capacity of DM Water	32	m^3 / hr
ost of DM water per Hour	575	Rs / hr		Cost of DM water per Hour	336	Rs / hr
nnual Operating Cost	5037000	Rs / year		Annual Operating Cost	2943360	Rs / yea
otal annual operating cost	5301902			Total annual operating cost	3099989	
TAC	**5339729**	**Rs / year**		**TAC**	**3137721**	**Rs / year**
Regeneration-reuse				***Regeneration-recycling***		
xed cost	1131707			fixed cost	1232776	
xed cost / service life	113171	Rs / year		fixed cost / service life	123278	Rs / yea

operating cost per year				**operating cost per year**		
/er cost per year	105120	Rs / year		power cost per year	58867	Rs / year
:t of DM Water	9	Rs / m^3		Cost of DM Water	8.5	Rs / m^3
›acity of DM Water	21.5	m^3 / hr		Capacity of DM Water	12	M^3 / hr
:t of DM water per Hour	193.5	Rs / hr		Cost of DM water per Hour	102	Rs / hr
ıual Operating Cost	1695060	Rs / year		Annual Operating Cost	893520	Rs / year
al annual operating cost	1800180			Total annual operating cost	952387	
TAC	**1913351**	**Rs / year**		**TAC**	**1075665**	**Rs / year**
yback Period Calculations		**Reuse**	**Regeneration-reuse**	**Regeneration-recycling**		
al additional cost of fixed ital investment =Fixed Cost ›ase case – Fixed cost for dified approach (a)			753443	854512		
vice life (years)			10	10		
'age values			0	0		
ings in operating cost= al operating cost of base ≥ – Total operating cost for dified approach (b)			3501722	4349515		
ings in operating cost/ Total itional cost of fixed capital ≥stment (c)			75344.263	85451.16		
'ayback periods in years = (a / (b +c))			0.2106314	0.192676005		
'ayback periods in months			2.527577	2.312112059		

LIST OF RESEARCH PAPERS SUBMITTED

Sr. No.	Ref. No. /Manuscript No.	Title of Paper	Authors	Submitted to Journal	Status As on 23rd June-2008	Date of submission
1	RECYCL-D-08-00131	A process integration approach to industrial water conservation: A case study for an Indian Starch industry	Mihir Dakwala Bikash Mohanty R.Bhargava	Resources, Conservation & Recycling	Forwarded by Managing Special Issue Guest Editor Jiri Klemes, PhD. to reviewers	11th June-2008
2	JCLEPRO-D-08-00095	"A process integration approach to industrial water conservation for multicontaminant system: A case study for an Indian Starch industry"	Mihir Dakwala Bikash Mohanty R.Bhargava	Journal of Cleaner Production	Forwarded by Editor Prof. Dr. Donald Huisingh, Ph.D to reviewers	28th May-2008
3	WR-S-08-01429	"Waste Water Minimization Of Starch Industry Using Water Pinch Technology"	Mihir Dakwala Bikash Mohanty R.Bhargava	Water Research	Submitted to journal	20th June-2008
Poster presentation at international conference						
1	Poster selected	Glucose Hydrogenation using Raney Nickel Catalysts in Batch Hydrogenators of Different Capacities	Mihir Dakwala Bikash Mohanty R.Bhargava	GLS-8 IIT Delhi	Original paper submitted to *Journal of Chemical Engineering Science*	17th December-207