PROCESS INTEGRATION IN WASTE WATER MINIMIZATION

A DISSERTATION

Submitted in partial fulfillment 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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CANDIDATES'S DECLARATION

I hereby declare that the report which is being presented in this dissertation work "**PROCESS INTEGRATION IN WASTE WATER MINIMIZATION**" 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 Dec 2005 to June 2007 under the supervision of **Dr. Bikash Mohanty**, Professor, Chemical Engineering Deptt Indian Institute of Technology, Roorkee.

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

DATE: JUNE 05, 2007 **(SANDEEP I. SINGAL)**

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

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It is with great pleasure that I take this opportunity to bow my head in respect and gratitude for all those who helped me in making this dissertation a great success. I am in dearth of words to express myself in such a joyous moment

I take this opportunity to grace myself from the benign self of my teacher and guide, Dr.Bikash Mohanty, for ushering me from theoriticality to practicality and from plutonic to pragmatic ideas. No rhapsody or rhetoric eloquence can replace of what he had done for me and the way he has helped me in bringing out this dissertation. I will always be indebted to him throughout my life.

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SANDEEP I. SINGAL

ABSTRACT

Water is widely used in chemical process industries, for example in product preparation, product separation and product finishing, etc. We treat water system design as a problem of mass transfer i.e. from a contaminant-rich process stream to a contaminant- lean water stream.

The Water network design problems are tackled by a number of approaches such as Hierarchical design approach, Graphical approach and Mathematical Programming approach. In present work Graphical approach, based on the Pinch Technology is applied to design water- reuse networks.

The present study is related to the use of water resources to maximize water reuse, minimize waste water regeneration, reduce effluent treatment and design of optimal water network at minimum annual cost. The problem is tackled in two steps. During the first step, a feasible target is established by integrating streams and utilities based on the Pinch Technology. In the second step, a network is designed to satisfy the targeted parameters and finally water network is fine-tuned to get an optimal water- reuse network at minimum annual cost.

Generally water-system design network problems are of two types: the first type is related to the design of a water-system design network for a new plant which is in the design stage and second type is to retrofit an already existing water system network in a plant to reduce its consumption. These problems are computationally intensive and need specialized approach as for its solution.

The Pinch Technology and Graphical Approach for solving water-system network problems are specially attractive. It provides a considerable flexibility to the designer and allows him to participate in the decision taking process. It also saves the designer from setting up superstructures of equations and development of complex codes for solution. Due to these attractive features in the present work, three water-system design problems were taken from a fertilizer plant for its solution as discussed.

The first problem is related to water system design network in Urea Plant; second and third problems deal with water use in the Rectisole Plant and Steam Generation Plant respectively.

Two computer programs are developed in MATLAB and are run in a Pentium-IV, 933 MHz machine to target above problems for different values of stream input data.

For the first problem, the targeted value of minimum freshwater flow rate is 26.53 t/h. With the help of water-reuse design network, we see a reduction in fresh water consumption from 230.42 to 183.68 t/h (a 20 % decrease) and an associated reduction in wastewater generation from 154.99 to 112.41 t/h (a 28 % decrease) with an annual benefit of Rs. 2,29,900.

For the second problem, the targeted value of minimum freshwater flow rate is 166.42 t/h. With the help of water-reuse design network, we see a reduction in fresh water consumption from 384.36 to 191.44 t/h (a 50 % decrease) and an associated reduction in wastewater generation from 314.36 to 187.94 t/h (a 40 % decrease) with an annual benefit of Rs. 10,57,147.

For the third problem, the targeted value of minimum freshwater flow rate is 637.83 t/h. With the help of water-reuse design network, we see a reduction in fresh water consumption from 5430 to 4348 t/h (a 20 % decrease) and an associated reduction in wastewater generation from 3720 to 2698 t/h (a 28 % decrease) with an annual benefit of Rs. 2,76,300.

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NOMENCLATURE

SYMBOL	DEFINITION	UNITS
m	Mass Load of Contaminant	kg/h
Q_{proc}	Flow Rate of Process Stream	t/h
$C_{proc,in}$	Input Contaminant Concentration in Process Stream	ppm
$C_{proc,out}$	Output Contaminant Concentration in Process Stream	ppm
$C_{w,in}$	Input Contaminant Concentration in Water Stream	ppm
$C_{w,out}$	Output Contaminant Concentration in Water Stream	ppm
C_{regen}	Regeneration Contaminant Concentration	ppm
Q_w	Minimum Wash water Flow Rate	t/h
C_{pinch}	Pinch Concentration	ppm
C_0	Pinch Regeneration Concentration	ppm
f_{ws}	Minimum Water Flow Rate	t/h
m_{pinch}	Pinch Mass Load Contaminant	kg/h
$f_{i,in}$	Input Flow Rate of Stream	t/h
$f_{i,out}$	Output Flow Rate of Stream	t/h
$C_{i,in}^{\lim}$	Limiting Input Contaminant Concentration	ppm
$C_{i,out}^{\lim}$	Limiting Output Contaminant Concentration	ppm
N_{int}	Number of Concentration Intervals	---
N_0	Number of Mass-exchange Operations	---

f_{ap}	Minimum amount of Wastewater	t/h
N_{ws}	Total Number of Water Source	---
N_{ews}	Number of External Water Source	---
N_{iws}	Number of Internal Water Source	---
f_{regen}	Regenerated Water Flow rate	t/hr
RR	Removal Ratio in Regeneration process	---
C_j	Upper Limit Concentration of Mass Interval	ppm
$C_{in,\max,i}$	Maximum Inlet Concentration of Contaminant in Water for operation i	ppm
$C_{out,\max,i}$	Maximum Outlet Concentration of Contaminant in Water for operation i	ppm
f_i	Limiting Flow rate of operation i	t/hr
$f_{rejected,pinch,m}$	Flow rate rejected at the m^{th} Pinch	t/hr
f'_{in}	Flow rate to Regeneration Process	t/hr
f'_{out}	Flow rate from Regeneration Process	t/hr
C_{ws}	Concentration of Contaminant in Water Source	ppm
Δm_j	Mass of Contaminant exchanged in Mass Interval j	kg/h
$\Delta m_{cumulative,j}$	Cumulative mass exchanged until the end of Mass Interval j	kg/h
$\Delta m_{cumulative,l}$	Cumulative mass exchanged until the end of Mass Interval l	kg/h

CHAPTER-1

INTRODUCTION

The damaging effect of the chemical process industry on the environment is one of the greatest challenges facing industry throughout the world. Although industry accounts for approximately 16 % of the direct water, it often produces effluents, which contain toxins and other damaging pollutants. The damaging effect of industry is compounded by a low availability of water. The reduction of both the consumption of water and production of effluent by this economic sector is of vital importance to the protection of water resources and environment. The above factors have resulted in wastewater minimization becoming an important environmental issue to industry.

Preventing pollution requires designs that are intrinsically eco-efficient, and not designs that rely on end-of-pipe treatment. In order to implement cleaner production designs, the designer requires methods to investigate the implications of the various design possibilities. Process integration is a holistic approach to process design, retrofitting, and operation, which emphasizes the unity of a process.

Smith gave a generalized illustration of water use on a typical process site. Raw water is pre-treated before use in various processes such as washing, (e.g. vessel cleaning). In these processes water comes into contact with process materials, becomes contaminated, and is sent to wastewater treatment. Freshwater (treated raw water) may be upgraded in boiler feed water (BFW) treatment for use in the steam system. Wastewater is generated by ion-exchange regeneration, boiler blow down and condensate loss. Another source of wastewater is the cooling tower blow down. The various wastewater streams are then typically mixed, along with contaminated storm water, and sent to treatment. Industrial processes thus require water with a range of qualities, and produce a range of effluents, which allow the possibility of a hierarchical use of water.

Possible strategies for reducing the production of wastewater include:

- Re-use: wastewater from one process can be directly re-used in others, provided the level of contamination is sufficiently low to meet the requirements of the subsequent processes;
- Regenerative re-use: wastewater can be treated to reduce the levels of contaminants before being re-used in other processes. In this option, the water is not recycled to the process from which it came;

- Regenerative recycling: after regeneration, water can be recycled to the process from which it came. This is generally more difficult than re-use, because recycling tends to build up contaminants.

Pinch analysis is a process integration tool, which was first developed for the design of heat recovery systems during the late 1970s. Using the analogies between heat and mass-transfer, a similar approach was developed for the design of mass-exchange systems. This work formed the basis for the design of water-using systems that conform to the usage patterns envisaged by Smith. It took the design objective to be to minimize water consumption by maximizing the reuse of water, using a graphical technique Wang and Smith, which was termed Water Pinch Analysis. However the technique was difficult (although possible) to extend to accommodate the practical constraints and characteristics of water-using systems, such as multiple contaminants, flow rate constraints, piping costs, etc. The added desire to introduce cost optimization required that the problem be formulated using mathematical programming techniques. Water Pinch Analysis thus involves a set of systematic formal techniques to handle the complex problem of hierarchical water allocation to a system consisting of a number of processes, and choosing the best combination of strategies.

The present investigation is planned to address following objectives:

- To apply graphical approach to all problems in order to target and design optimal water- system network.
- To develop computer program to target a class of water-system design network problem.

CHAPTER-2

LITERATURE REVIEW

LITERATURE REVIEW

This Chapter begins by presenting brief outlines of the literature on the topic from several points of view and then reviews in more detail approaches, which were found to be particularly useful for the objective involved in this investigation.

2.1 DEVELOPMENT OF WATER PINCH ANALYSIS

Process integration provides a basis for analyzing and developing a design at a relatively early stage of its development by providing global insights of the process to the designer, coupled with methodical targeting and design procedures.

This point of view has lead to the development of process synthesis being defined as the discrete decision making activities of conjecturing which of the many available component parts one should use, and how they should be interconnected to structure the optimal solution to a design.

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. Linnhoff *et al.* (1994) used a graphical approach 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. Pinch Technology can also be applied in retrofit situations however additional restrictive parameters are introduced.

Pinch analysis was initially developed for the optimization of heat exchanger networks following the methodology proposed by Linnhoff and Flower, 1978.

More recently, various people to extend the pinch concept to waste water minimization have used the analogies between heat conservation and wastewater minimization. Takama *et al.* (1980) approached the problem of optimal water allocation in a petroleum refinery. In their approach a superstructure of all possible reuse and regeneration opportunities was generated. This superstructure was then optimized and the uneconomical features of the design removed. Takama also considered the possibility of regeneration of wastewater. El-Halwagi and Manousiouthakis (1989) adapted the methodology developed by Linnhoff and Hindmarsh (1983) for heat exchanger networks, in order to deal with mass exchange of a single contaminant, between a set of rich process streams and a set of lean process streams. In order to do this they defined a minimum allowable concentration difference that applied throughout the mass exchange network. Since the problem of matching the rich and lean streams is combinatorial they introduced the notion of mass exchange network (MEN) synthesis.

This approach was later automated and modified to include regeneration. In this approach a procedure was developed which allowed the simultaneous synthesis of primary mass exchanger networks and their associated regenerative networks. The regenerative network was aimed at regenerating any recyclable lean streams. The proposed procedure deals with the problem in two stages. The first stage involves the solving of a mixed-integer non-linear programming in order to minimize the cost of mass separating and generating agents. This problem was formulated using thermodynamic constraints. Its solution then allows the location of all the pinch points as well as the optimal flow rates of the lean and regenerative streams. The second stage of the procedure allows the number of units in both networks to be minimized. Solving a mixed integer linear programming problem does this. El-Halwagi *et al.* (1992) then applied this approach to phenol treatment in petroleum refinery wastewater.

Wang and Smith (1994 a) 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. Wang and Smith constructed 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. They then 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. Wang and Smith also considered the case where more than one contaminant is present and extended their methodology to deal with this situation. They also considered the implications of regeneration of wastewater.

In a later paper Wang and Smith (1995 a) 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.

2.2 WATER REUSE NETWORKS

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 procedure
- Pinch technology technique
- Mathematical programming tool

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. Pinch analysis approaches, which are graphically based, are of limited use when large systems and multiple contaminants are involved. Wang and Smith have developed the methodology for water networks and deal with networks involving multiple contaminants, reuse, regeneration as well as fixed flow rate constraints and multiple water sources (Wang and Smith, 1994a, Doyle and Smith, 1997).

Doyle and Smith (1997) presented a mathematical programming approach for targeting maximum water reuse in the processing industry. The approach proposed by Doyle and Smith involves a combined approach of linear and non-linear programming - the linear programming solution is used as an initial estimate for the non-linear programming problem. Although the case study presented by Doyle and Smith consisted only of fixed-mass-load operations (Fig.2.1), the mathematical programming approach may also be applied to operations with more complex contaminant loading models.

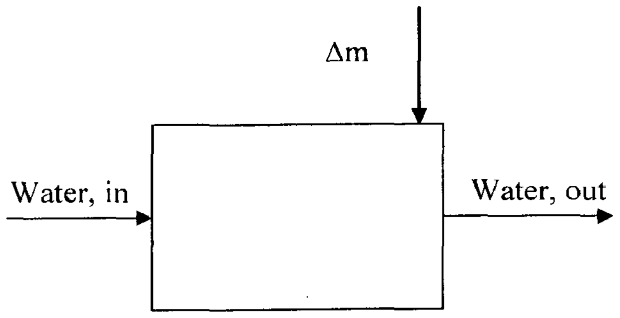


Figure 2.1. A fixed-mass-load operation

The state of the art of mathematical programming, as applied to the automated design, integration and operation of chemical processes, has been reviewed by Grossmann *et al.*, (1999).

2.3 REAGENT REUSE NETWORKS

While the design of water reuse networks is well documented, no references seem to cover reagent networks. The development of theory covering hydrogen networks has been carried out by Towler *et al.*, (1996). The method presented is graphically based and another form of the Two Composite Method. Although formulated for hydrogen, the method is not specific in what material is under consideration and may be extended to reagents.

2.4 SINGLE CONTAMINANT, GRAPHICAL APPROACH TO PINCH ANALYSIS

Analogies between heat and mass transfer have been used to extend the concept of pinch analysis to encompass waste minimization and pollution prevention. Techniques have been developed in order to design optimal mass exchanger networks (MEN). These minimum flow rate networks minimize the amount of fresh water consumed and waste water produced.

El-Halwagi *et al.* (1989-1997) presented several methodologies for the design of MENs, pioneering the extension of the pinch analysis from thermal to mass integration. A brief overview of their work is presented in the first part of this chapter.

Wang and Smith (1994a) developed an approach, which involves the generation of a single composite curve, which is used to set minimum flow rate targets. This approach is presented in the second part of this chapter, closely following their original ideas and examples in order to generate as much conceptual insight as possible into their ideas behind water based pinch analysis.

2.4.1 El-Halwagi (1989-1997)

The focus of El-Halwagi's work is pollution prevention through source reduction and recycle/reuse but El-Halwagi (1997) concedes that the four waste management activities namely source reduction, recycle/reuse, end-of-pipe-treatment and disposal via post process activities e.g. deep well injection, need to be integrated and reconciled. The most effective design methodology determines the extent to which each of these options should be used. The majority of the theory generated by El-Halwagi and co-workers focuses on the application of process integration for pollution prevention with a large emphasis on mass integration techniques.

El-Halwagi (1997) considered the synthesis of optimal mass exchanger networks. Defining a mass exchanger as any direct-contact mass-transfer unit that employs a lean phase (MSA, Mass Separating Agent) to selectively remove certain components from a rich phase. The lean phase should be partially or totally immiscible in the rich phase. The components are redistributed among the phases and this leads to a depletion of the rich phase and an enrichment of the lean phase. The majority of his work concentrates on counter current systems because of their efficiency and industrial importance.

The mass exchange processes category includes processes falling into the following categories: liquid-liquid extraction, liquid-gas absorption (scrubbing), liquid-solid absorption, ion exchange, leaching and stripping. Hence examples of mass separating agents (MSAs) are solvents, absorbents etc.

El-Halwagi (1997) described the problem of synthesizing Mass Exchanger Networks (MENs) as: given a number N_R of waste (rich) streams (sources) and a number N_S of MSAs, it is desired to synthesize a cost effective network of mass exchangers that can preferentially transfer certain undesirable species from the waste stream to the MSAs.

The designer based on the limitations of each application assigns the target compositions of the undesirable species. The MEN synthesis task then attempts to provide the optimal solutions to the following questions.

1. What mass exchange operations should be used?
2. Which MSAs should be used?
3. What is the optimal flow rate of the MSA?
4. How should the MSAs be matched to the waste streams?
5. What is the optimal system configuration?

The designer needs tools that systematically target the optimum solutions to these questions before detailed process design takes place. El-Halwagi identifies two useful targets; however these targets are normally incompatible. The first of these targets, the minimum cost of the MSAs, involves integrating the thermodynamic constraints of any given problem with the cost data for the individual MSAs. From this it is possible to identify both the minimum cost of the MSAs and the minimum flow rate needed to satisfy any given mass exchange duty. The second target involves identifying the minimum number of mass exchange units. This is an attempt to minimize the fixed cost of any given network, as the cost of a unit is normally a concave function of the unit's size. El-Halwagi and Manousiouthakis (1989) related the number of units to the total number of streams by the following expression.

$$U = N_R + N_S - N_i \qquad \text{.......} (2.1)$$

Here N_i is the number of independent synthesis sub problems, normally one.

Optimization of the final network design is achieved by trading off the minimum operating cost against the minimum number of units, this is translated as a trade-off between fixed cost (capital outlay) and operating costs (cost of MSAs). Commonly this trade off is achieved by three methods.

In the first method the minimum allowable composition difference is used as a trade-off point between the fixed and operating costs (similar to trading off of the minimum temperature difference against network cost in thermal pinch analysis). An increase in the minimum allowable concentration difference results in the increase in the MOC (minimum operating cost) of the network.

The second method of achieving this trade-off is the mixing of waste streams. This decreases the number of mass exchangers and hence the fixed cost. However at the same time mixing results in a process MSA or a low cost external MSA becoming infeasible and hence the MOC of the network increases.

The third method involves the use of mass load paths El-Halwagi and Manousiouthakis (1989). This path is a continuous connection that starts with an external MSA and concludes with a process MSA. By shifting the loads along this path, one can add an excess amount of external MSA and remove an equivalent amount of process MSA. These results in the elimination of mass exchangers, but incurs a penalty in the form of increased operating costs. In order to decide whether or not to employ a mass load path, the fixed cost saving achieved by the elimination of mass exchangers should be compared to the additional operating cost incurred.

The first step in mass integration is the development of a global mass allocation of the whole process from a species viewpoint. For each pollutant there are sources (pollutant rich streams) and process sinks (treatment facilities, reactors etc.). Streams leaving the sinks become sources and each sink/generator can be manipulated to affect the flow rate and composition of what each sink can accept and discharge. Effective pollution prevention can be achieved through the combination of a number of concepts namely stream segregation, mixing, inception, and recycling and sink/generator manipulation.

2.4.2 Wang and Smith (1994-1995)

This series of papers has been very influential in shaping the theory of water pinch analysis.

2.4.2.1 Basic Methodology

According to Wang and Smith (1994 a) there are four general approaches to waste minimization:

1) **Process Changes** - This involves reducing the inherent demand of a process for water.
2) **Reuse** - Wastewater can in some cases be reused directly in other operations, provided the level of contamination introduced in the previous operation does not interfere with the process. It may require blending of wastewaters or the blending of wastewater with fresh water.
3) **Regeneration Reuse** - Wastewater can be regenerated by partial treatment to remove contaminants, which would prevent its reuse, and then its reuse in other operations. It may not be reused in the operation that generated the waste in the first place, as this recycling will eventually lead to build up within the process. The regenerated water may be blended with other wastewater or with fresh water.
4) **Regeneration Recycling** - Wastewater can be regenerated to remove contaminants that have built up; it is then recycled back to the process that generated the waste originally.

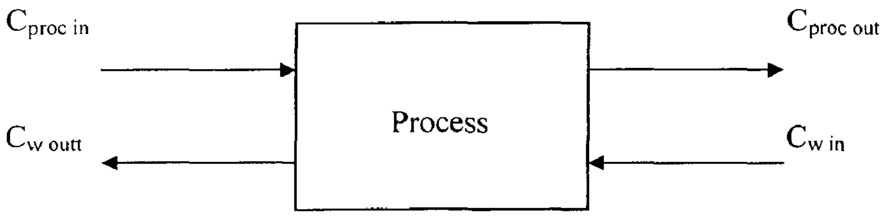


Figure 2.2. The water-using process considered by Wang and Smith

Wang and Smith initially considered the water-using process in which a single contaminant is removed from a process stream using water as in Fig.2.2. Different water flow rates and contaminant levels can solve the same problem. In order to maximize the possibility of water reuse from other operations the inlet concentration to particular operation is set as high as possible, then by specifying the maximum possible outlet concentration, the minimum water flow is defined. This case is known as the limiting case, any water supply line below this (and hence water flow rate above) will satisfy the process requirement. These maximum inlet and outlet concentrations might be fixed by:

1) Minimum mass transfer driving force;
2) Maximum solubility;
3) Corrosion limitations;
4) Fouling; etc.

The limiting water profile is used in the analysis because this approach can applied to operations that are very different in nature, and the use of the limiting case allows all the processes to be treated in a standard way.

The Wang and Smith procedure begins with the generation of a table of limiting process water data. This is done for any given process by:

1) Specify the mass load of contaminant (m) to be removed from the process stream.

$$m = Q_{proc} \times \left[C_{proc,in} - C_{proc,out} \right] \qquad \text{...... (2.2)}$$

2) Specify the maximum allowable contaminant concentration $C_{w,in,\max}$ in the feed water or in the outlet $C_{w,out,\max}$ determined by process or equipment limitations such as precipitation or corrosion potential.
3) Calculate the maximum concentration of the contaminant in the water outlet stream or in the water inlet.
4) Calculate the minimum wash water flow for each process.

$$Q_w = \frac{m}{C_{w,out,\max} - C_{w,in,\max}} \qquad \text{......(2.3)}$$

This is repeated for each process and the results are tabulated in the format of the limiting data presented in Table 2.1.

Table 2.1. Limiting process water data (after Wang and Smith (1994a)).

Process number	Mass load contaminant (kg/h)	$C_{w,in}$ (ppm)	$C_{w,out}$ (ppm)	Water flow (kg/h)
1	2	0	100	20000
2	5	50	100	100000
3	30	50	800	40000
4	4	400	800	10000

The limiting data presented in Table 2.1 are those given as an example by Wang and Smith (1994 a) and are used here to illustrate the single contaminant procedure. For dilute systems mass transfer is assumed to be a linear function of concentration. For concentrated systems each curve can be approximated as a series of linear segments.

The limiting water data are then plotted as limiting profiles, Fig. 2.3, (note the figures are not to scale). These limiting profiles are then used to construct a limiting composite curve. Combining the operations within concentration interval generates this composite curve. This curve now represents how the entire system would behave if it was a single water using process and incorporates the process constraints directly.

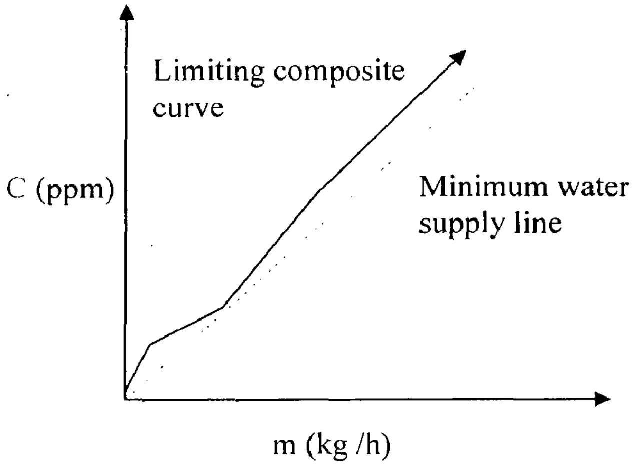


Figure 2.3. Limiting water profiles and composite curve for the problem of Table 2.1

The composite curve shows the critical sections of the plant. These critical sections of the plant require close attention in order to minimize the water flow rate.

This composite curve is then matched to a water supply line. The inlet contaminant concentration of the water supply line is assumed to be zero and hence the water supply line will always pass through the origin.

Any line through the origin below the composite curve represents a water supply flow rate that will satisfy the system. The minimum water supply line, representing the minimum water flow rate, is the line that which just touches the composite curve. Each point where the supply line touches the limiting profile creates a pinch in the design. There will generally be at least one pinch point. The inverse of the gradient of this water supply line then specifies the target for the minimum water flow rate.

It is important to note that at the pinch point the case of zero mass transfer driving force does not occur. This is because minimum mass transfer driving forces have already been built into the limiting data.

Having specified the minimum water flow rate, Wang and Smith then present two methods for the network design. The first method maximizes the concentration driving forces in the resulting design and takes full advantage of the concentration difference between the limiting composite curve and the water supply line. The strategy involves dividing the limiting composite curve into vertical mass load intervals at each point where the gradient changes. Wang and Smith then use the grid diagram for network design that is a concept initially developed by Linnhoff and Flower (1978).

While this produces a design, which meets the minimum water flow rate, it also leads to unnecessary complexity. Wang and Smith solved this problem by identifying independent loops in the design and then breaking them. This leads to a far less complex design that still uses the minimum water. This procedure is analogous to that introduced by Linnhoff and Hindmarsh (1983), used.

In regions far pinch point the driving forces between the composite curve and the water supply line are large and it is possible to break loops in the design without incurring a penalty in the form of an increased water flow rate. Breaking loops around the pinch does, however introduce an increased use of water.

The second method introduced by Wang and Smith ensures the minimum numbers of water sources are used. This second method involves following concentration intervals instead of mass load intervals.

In each match only sufficient water is used to maintain network feasibility i.e. the minimum amount of water required by the process is used; the unused water is bypassed to be mixed in later. The design procedure then follows that of the first method including identification and breaking of loops in the initial design. This design strategy combines the minimum flow rate and network simplicity by exploiting bypassing and mixing. It produces a design with only a single water source that still achieves the minimum flow rate target.

2.4.2.2 Regeneration Reuse

Wang and Smith (1994 a) consider first the placement of regeneration processes for a single contaminant when reuse but not recycling is allowed. The water supply line also shows a regeneration process. The water is taken to concentration C_{regen} to the limiting composite curve. It then enters a regeneration process, which brings the level of contaminant down to a concentration C_0.

The mass transfer is completed with regenerated water. It is assumed that the flow rate of water before and after regeneration is the same hence; the water supply lines before and after regeneration have the same slope. If there is a significant change in flow rate before and after regeneration, the construction is easily modified to take this into account by relating the slopes to its flow rate characteristics.

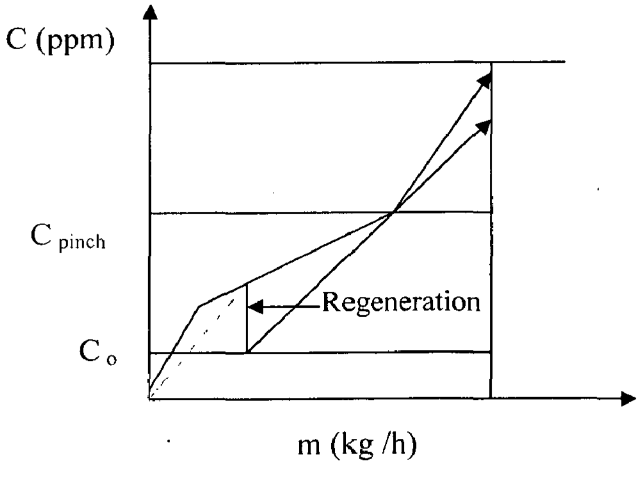


Fig.2.4. Placement of a water regeneration process relative to pinch

The placement of the regeneration process as shown in Fig.2.4 clearly brings a reduction in flow rate. To determine whether the flow rate is minimized it is necessary to create a composite of the water supply lines before and after regeneration and match this against the limiting composite curve as shown in Fig.2.4.

The composite water supply line in Fig.2.4 just touches the limiting composite curve, which seems to indicate that the water flow rate with regeneration is minimized. However, the dotted line shows what would have happened if the water had been allowed to reach a higher concentration before entering the regeneration, there is clearly a gap between this line and the composite curve indicating that the water flow rate is not minimized.

The outlet of the regeneration process is specified (C_0) and the flow rate before and after regeneration is unchanged. This seems to be infeasible, since the water supply line crosses the limiting composite curve. Once again feasibility can only be determined by creating a composite of the water supply lines before and after regeneration. The placement with regeneration at pinch concentration is seen to be feasible and the water flow rate is minimized.

By allowing the water supply line to achieve pinch concentration before regeneration allows the designer to achieve both the minimum water flow rate and the minimum concentration reduction in the regeneration process. A simple mass balance calculates the water supply flow rate:

$$f_{ws} = \frac{m_{pinch} - f_{ws} \times C_{pinch}}{C_{pinch} - C_0} \qquad \text{......(2.4)}$$

Returning to the first example used to illustrate the single contaminant approach and applying regeneration with a unit capable of reducing the contaminant level to 5 ppm. The minimum water flow rate (Equation 2.4) is 46.2 t/h. To design with regeneration the same design procedures are used as before, however above the pinch only regenerated water must be used. Below the pinch both regenerated and unregenerated water can be used.

Fig.2.5 shows the design with regeneration after the breaking of loops. Although process 2 is contacted with water before and after regeneration, there is no recycle. Different parts of process 2 are serviced by different sources of water.

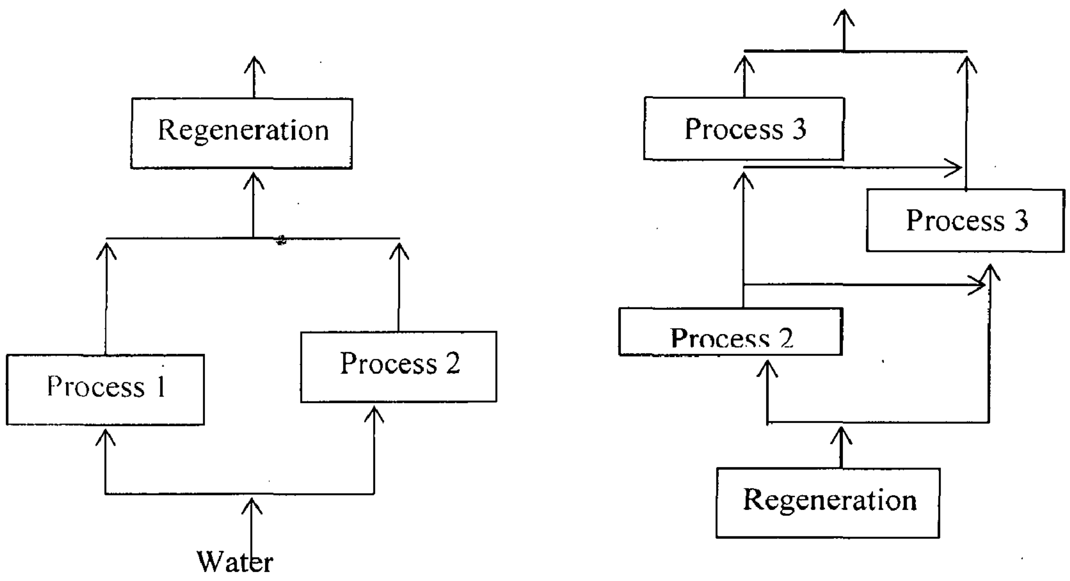


Fig. 2.5. Final Network design for minimum water use with regeneration.

Situations can arise in which partial regeneration of water is called for. In these situations the slope before regeneration (f_{ws}) is equal to that after regeneration (f_{regen}), indicating total water regeneration. The process cannot support a lower flow rate before regeneration but can support a lower flow rate after regeneration. The unregenerated water with flow rate $\left(f_{ws} - f_{regen}\right)$ is also available above the pinch concentration. A simple mass balance gives the regenerated water flow rate:

$$f_{regen} = \frac{m_{pinch} - f_{ws} \times C_{pinch}}{C_{pinch} - C_0} \qquad \text{......(2.5)}$$

A regeneration process must perform to either of the following:

(i) A minimum outlet concentration of C_0,

$$C_{out} < C_0 \qquad \text{......(2.6)}$$

(ii) A removal ratio RR,

$$RR = \frac{f_{in}^{i} \times C_{in} - f_{out}^{i} \times C_{out}}{f_{in}^{i} \times C_{in}} \qquad \text{......(2.7)}$$

It is possible to apply the principles developed for regeneration with a specified outlet concentration to a regeneration process defined by removal ratio. Mass removal in the regeneration process allows for water re-use in operations with $C_{in,\max,j} < C_{pinch,j}$. In other words, the same water can be used twice in the interval $[C_0, C_{pinch,j}]$.

Wang and Smith (1994a) calculated minimum water flow rate, f_{ws} by considering the mass balance before the pinch:

$$\Delta m_{cumulative,pinch,j} = f_{ws} \times \left(C_{pinch,j} - C_{ws}\right) + f_{regen} \times \left(C_{pinch,j} - C_0\right) \qquad \ldots\ldots(2.8)$$

It is possible to apply the principles developed for regeneration with a specified outlet concentration to a regeneration process defined by removal ratio.

2.4.2.3 Regeneration Recycling

If recycling is allowed, it is possible to reduce the supply flow rate below that for reuse only, with the flow rate reduced to that dictated by the slope of the limiting composite curve below C_0. If this flow rate is allowed to reach C_{pinch} and regenerated, then there is insufficient water to satisfy the problem.

This is an interesting concept, but does not apply when the exit stream from the process is not available for recycling i.e. the exit stream now appears in a final product, or when the 'contaminant' is a desirable species. In such a case, any regeneration is actually destruction of a final product or a valuable reagent. This has some serious implications for almost all the procedures that are available, especially when applied to a real industrial case, since this introduces a further set of considerations to the problem.

2.4.2.4 Single Operations with Fixed Flow rates

Wang and Smith (1995a) investigated single operations with fixed flow rates and the use of pinch technology to minimize this flow. Consider an operation with a maximum inlet concentration of $C_{in\ max}$ and a maximum outlet concentration of $C_{out\ max}$ and water flow rate fixed at f_L.

It is possible that during the construction of the water supply line that the minimum water flow rate suggested is lower than the required flow rate for the process. This may suggest that this minimum flow rate is now infeasible. However the solution to this problem is relatively simple and takes the form of local recycling around the offending operation. A simple mass balance proves that the inlet concentration to the process is within the limit.

Whether or not an operation can be split into parts depends very much on the nature of the operation. For example, a multistage washing operation can be readily split, whereas a steam stripping cannot be. The operation has been split such that each part has a flow rate requirement which is less than or equal to $f_{\min}$. Here part 1 of the operation has been taken to have a flow rate equal to $f_{\min}$, part 2 taking the remainder of the flow rate.

2.4.2.5 Multiple Operations with Fixed flow rates

Consider now the limiting composite curve in Fig.2.6, in which all of the operations, which comprise the composite curve, have a fixed flow rate. A water supply line has been matched against the limiting composite curve. The construction has also been split into vertical mass load intervals. In mass load intervals II and I the total flow rate requirements exceed $f_{\min}$. This implies that the straightforward design method will produce an infeasible design.

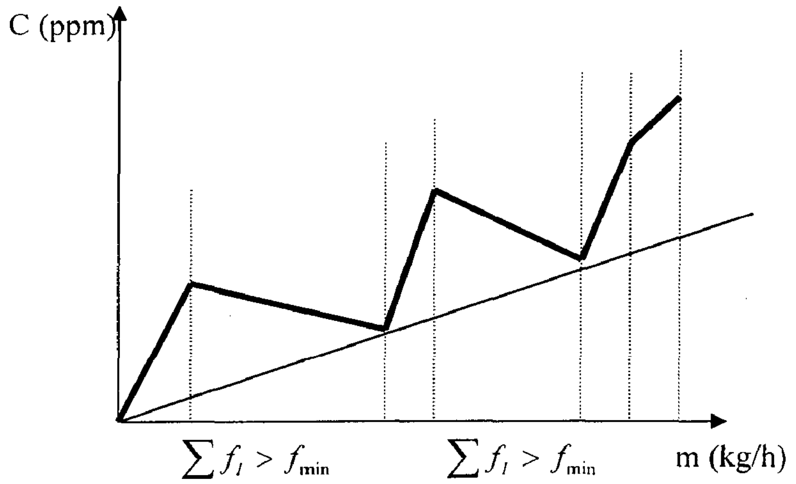


Figure 2.6. Composite curve of several fixed-flow-rate processes

If local recycling is not acceptable it is possible to design using the philosophy adopted for reuse with single operations. The difference now is that the operation is naturally split since the overall system already consists of several operations. As long as each operation requires a flow rate less than or equal to $f_{\min}$ there is no need to split individual operations. If needs be individual processes can be split into parts satisfying the constraint that each operation or part-operation should require a flow rate less than or equal to $f_{\min}$. The order of reuse must also be in increasing order of flow rate requirement. A simple mass balance can demonstrate the feasibility of the design.

If local recycling is not desirable and operations cannot be split, then the target for each interval can no longer be $f_{\min}$. Since each operation for reuse must have a flow rate requirement less than or equal to $f_{\min}$, for reuse, if operation splitting is not allowed for the interval then the target flow rate f_T given by:

$$f_T = \max(f_{\min}, f_i) \qquad \ldots\ldots(2.9)$$

Where the steepest water supply line gives $f_{\min}$, which can be matches against the Limiting composite curve and $f_{\min}$ are the flow rate requirements for the individual operations. Note that equation 2.9 only guarantees that operation splitting within any individual interval is not necessary. It might still be necessary to split an operation between intervals.

Wang and Smith (1995 a) combined the insights gained in their first paper (1994 a) with their ideas on splitting operations and local recycling and presented a design method, which produced minimum flow rate designs. This design method closely follows that presented in the previous paper, but satisfies flow rate constraints by one of the methods discussed above.

To adapt the approach above for single contaminants to the placement of regeneration processes with multiple contaminants, a reference contaminant is chosen, and the limiting composite curve is constructed based on that contaminant (using shifting where necessary).

2.4.2.6 Multiple Sources of Fresh Water

Consider a situation where there are three sources of freshwater available, demineralised water, potable water and bore hole water. The highest quality is demineralised water and the lowest purity is borehole water. Potable water is available with a concentration of contaminant C_{pot}.

Demineralised water is substituted by potable water above C_{pot} . The slope of the limiting composite curve below dictates the minimum amount of demineralised water which is necessary. The difference in slope between the water supply line below and above C_{pot} indicates the amount of potable water.

2.4.2.7 Processes with a water loss

Many processes involve a water loss. Operations such as boiler feed water, cooling tower make-up and reactor feed water are not mass transfer operations but they can, in some circumstances, use spent water from previous mass transfer operations. The involvement of a water loss in these processes means that some, or perhaps all of the water fed to these processes, does not become available for reuse in other processes. Wang and Smith extended their methodology to cover this situation.

2.4.3 Olesen and Polley (1997)

Olesen and Polley (1997) presented a new procedure for the design of water networks for systems involving single contaminants. It is an extension of Wang and Smith's conceptually based design strategy and uses a Load Table, which shows the distribution of duties about Pinch and the minimum water needs for each operation. The procedure also uses the concept of Remaining Problem Analysis.

2.4.3.1 Classification of Operations

The network design procedures reported to date all use some level of numerical analysis. Olesen and Polley (1997) consider these design strategies to be unnecessarily complex. The design of networks for problems having up to four or five individual operations can generally is satisfactorily achieved by inspection. They considered all the possible operations that may be present in a system and classified them into distinct types each of which has distinct design implications.

Type 1. Operations that require fresh water and terminate at the Pinch

These streams can be assigned a fresh water flow rate that provides for a spent water concentration that equals the pinch concentration. This is the minimum flow required for the operation and it does not prejudice the minimum water target. The operation can then be removed from further consideration. This type of operation should be dealt with first in order to reduce the size of the design problem.

Type 2. Operations that require fresh water and terminate above the Pinch.

These streams can be treated in the same manner as type 1 streams. Fresh water is assigned at the minimum flow rate. The minimum flow rate target is not prejudiced. The operation can be removed from further consideration.

Type 3. Operations that require fresh water and terminate below the Pinch.

The spent water from these operations must be reused in another operation prior to the Pinch. Having dealt with operations of types 1 and 2 the presence of operations of this type must be flagged before other types of operation are addressed. However, no firm decision on how these operations fit into the network can be taken without reference to the others. The flow of fresh water used for the operation will depend on how the operation is subsequently matched with others.

Type 4. Operations that can use spent water from other operations and terminate below the Pinch.

Again, the spent water from these operations must be reused in another operation prior to the Pinch. If only one operation of this type is present in the system fresh water should be used .The water flow rate will depend on how this operation is subsequently matched with others. If more than one of these operations is present the designer may need to consider using spent water from one operation to feed another.

Type 5. Operations that can use spent water and terminate at the Pinch.

If the system does not contain operations of types 3 and 4, fresh water can be used for this type of operation. The treatment is the same as for a type 1 operation; otherwise it may be necessary to use spent water for this type of operation.

Type 6. Operations that can use spent water and terminate above the Pinch.

This is the most difficult type of operation to satisfy. Care and consideration must be taken with regard to both the pinch concentration and the maximum water outlet concentration. The water flow will be limited by the duty on one or other side of the pinch. The designer should start by determining the minimum water flows on either side of the pinch. The minimum water flow required above the pinch is estimated by dividing the above pinch load by the difference between the maximum water outlet concentration and the pinch concentration. The minimum water flow required below the pinch can be determined from the below pinch load and the difference between the water inlet and pinch concentrations. The water used for the operation may be fresh water but it could be spent water from a type 3 or 4 operation. The larger of these two water flows is the minimum required for the operation and is subsequently the elected value.

If the above-pinch load is controlling, it is the maximum allowable water outlet concentration that must be met. The required water inlet concentration is then determined from the operation's load and water flow rate. If the below-pinch load is controlling, it is the inlet water concentration that is specified. The subsequent water outlet concentration is computed from the load and water flow.

2.4.3.2 Load Table for Network Design

From the discussion of types of operations (particularly that relating to operations of type 6), it is clear that a table listing the above and below pinch contaminant loads and potential flow/concentration profiles would be a useful tool. Such a table is given in Table 2.2 for the single contaminant design problem introduced by Wang and Smith (1994 a). The composite curve and minimum water supply line are constructed using the procedure described by Wang and Smith (1994 a).

Table 2.2. Load table for Wang and Smith's single contaminant problem

			Below the pinch			Above the pinch		
Operation	Type	Total load (kg/h)	Load (kg/h)	Min.flow (t/h)	C_{out} (ppm)	Load (kg/h	Min.flow (t/h)	C_{in} (ppm)
1	1	2	2	20	100			
2	5	5	5	50	100			
3	6	30	2	20	1500	28	40	50
4	7	4				4	5.7	100

This load table is constructed by considering the operation classification (types 1 to 7), total contaminant load, above and below the pinch loads, above and below the pinch minimum water flow rate for each operation as well as the related inlet and outlet concentrations. (The data defining this problem are given in Table 2.1)

The design for minimum water flow rate is as follows:

Operation 1 is of type 1 and tackled first. The fresh water flow required for the operation is 20 t/h. There are no operations of types 3 or 4. Operation 2, which is of type 5, can be treated in the same way as a type 1 operation. Fresh water is used at a flow rate of 50 t/h. Attention is now directed at operations of type 6. Only operation 3 falls into this category. The minimum flow rate required for the above pinch part of the operation will be 40 t/h. Taken over the full operation the maximum outlet concentration of 800 ppm is reached if the water has an inlet concentration of 50 ppm. The minimum water flow rate for the below pinch part of the operation (assuming that fresh water is used) is 20 t/h. It is seen that the above-pinch part of the operation is limiting. The operation is set as having a flow of 40 t/h at an inlet concentration of 50 ppm. The available freshwater supply is 20 t/h.

This can be mixed with spent water from operation 1 (flow 20 t/h, concentration 100 ppm) to provide the exact-flow and the required concentration. The only operation remaining is operation 4. It is easily satisfied using the spent water from operation 2. The final design (generated by inspection and meeting the minimum water target of 90t/h) is shown in Fig.2.7. Wang and Smith, namely the use of a grid diagram followed by loop breaking procedures and finally conversion to a conventional flow sheet, achieve this design without the complications of the design methods presented.

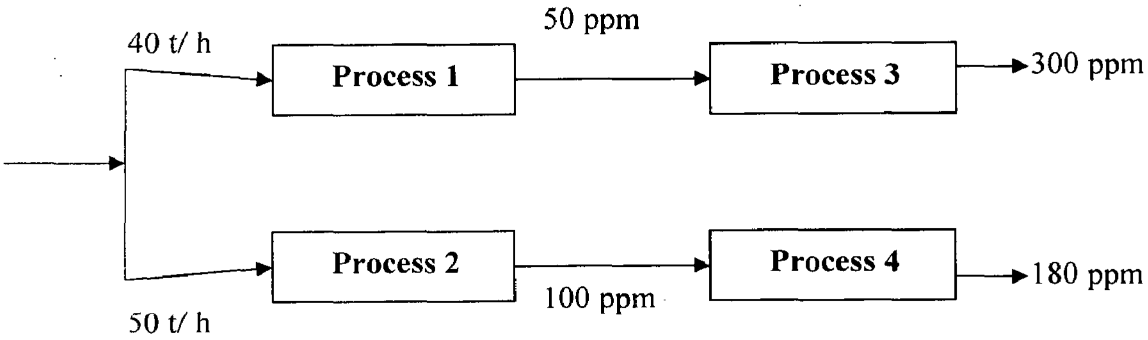


Fig.2.7: Final design for Wang and Smith's single contaminant problem

The load table concept is a simplification of the Wang and Smith procedure and one would expect it to demonstrate the same limitations as the parent technique. It is however a useful concept and should be kept in mind when tackling a real problem.

2.4.3.3 Remaining Problem Analysis

For larger more complex problems, the designer can be guided using a procedure that could be considered to be analogous to the Remaining Problem Analysis used in thermal pinch.

1. An element of the design is developed.
2. The operation is removed from the data set.
3. Spent water from the operation is introduced into the data set as a secondary source of fixed flow.
4. Targeting is reapplied to the new data set.

2.5 SELECTION OF CONTAMINANTS

Within the context of a water pinch investigation, the waterborne species, which restrict the reuse of water in the system, are termed contaminants. The identification of these species is done simply by questioning what prevents the reuse of a water stream in a particular area of the system. Contaminants may be single entities such as ions or molecules (e.g. Ca_{2+} ions) or aggregated group's e.g. total dissolved solids (TDS).

In some cases it becomes necessary to distinguish between contaminants and reagents, which are introduced deliberately (this can be seen as another aspect of the process/utility question). Some like NaOH may be a reagent in one part of a process, and a contaminant in another. One may have to consider the part of the system where a solute is a reagent as an invariant part of the process, i.e. excluded from the pinch analysis.

2.6 SOURCES OF DATA

Once the significant processes and their inter-process connectivity have been established, the water mass flow rates must be determined. There are several sources for flow data:

1) Existing plant records. This is the most obvious source. Sophisticated facilities may have computerized monitoring of process flows throughout the plant.
2) Design data. Where available and still reasonably relevant, the original design figures can be used to estimate missing data. However, of all the aspects of a process, the water systems are perhaps the most likely to be altered as circumstances change.
3) Control data. There are several types of control settings that may be of interest, two are mentioned here:

   - Ratio control: Flows of inter-process streams dependent on others will have a corresponding control valve setting. For example, the mass flow of dilution water required for dilution of reactor feed may be dependent on the flow rate of raw materials.

   - Composition: Valve settings that respond to changes in stream composition or density. For example, the mass flow of steam to an evaporator may be dependent on the density of the inflow.

4) Unit operation data. Plant operations can offer a wealth of various types of flow rate data and relationships:

-Through flow: The typical flow rate that the operation is designed to handle may be used;

- Flow relationships: Design relationships between outlet and inlet flow rates may be useful, such as splitting fractions of inlet streams;

Flow losses: Some losses are inherent to the process and must be taken into account such as leaks, evaporation rates, overflows, etc.

5) Manual measurements. Many smaller streams or non-process streams may not be monitored. Sometimes these streams cannot be inferred from mass balance calculations.

2.7 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 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.

HEURISTIC TECHNIQUES

These procedures are based on rules of thumb rather than a formalized approach - see Liu 1999 (Liu 1999). No experience was gained with use of these techniques during this investigation.

GRAPHICAL TECHNIQUES

Two methods are prominent: the approach initiated by Wang and Smith (1994 a, 1994 b, 1995 a,) and that proposed by Beuhner (1996).

The Wang and Smith method is generally suited to simple systems involving single contaminant mass-exchange type operations. The technique has been extended to deal with multiple contaminants but the procedure becomes increasingly cumbersome for greater numbers of contaminants. The technique also breaks down when no mass-exchange operations are present in the system.

PROBLEM STATEMENTS

In this Chapter some water system design problems, which have been taken from a Fertilizer Plant, are formulated which will be targeted and designed by Graphical approach based on Pinch Technology.

3.1 WATER MINIMIZATION IN UREA PLANT (PROBLEM 3.1)

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

Input Data: -

The Stream data is shown in the Table 3.1 given below.

Table 3.1. Stream Data for Water Minimization for Problem 3.1

Operation	$f_{i,in}$	$f_{i,out}$	$C_{i,in}^{\lim}$	$C_{i,out}^{\lim}$
i	t/h	t/h	ppm	ppm
1 (DW)	14.59	25.83	6.0	322.7
2 (CTA)	58.33	15	6.4	15.6
3 (CTB)	58.33	15	2.1	10.8
4 (SC)	2.50	2.5	20.0	207.0
5 (FW)	1.75	1.75	0.0	3.0

Expected output: -

To design water-reuse network for this problem and make a cost/benefit analysis of the selected water-reuse options. The solution of this problem is given in section B.1 of Appendix-B.

3.2 WATER MINIMIZATION IN RECTISOLE PLANT (PROBLEM 3.2)

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

Input Data: -

The Stream data is shown in the Table 3.2 given below.

Table 3.2. Stream Data for Water Minimization for Problem 3.2

Operation	$f_{i,in}$	$C_{i,in}^{\lim}$	$C_{i,out}^{\lim}$
i	t/h	ppm	ppm
1(EC1)	36.36	25	80
2(EC2)	44.31	25	90
3(EC3)	22.86	25	200
4(SC)	60.00	50	100
5(CT1)	40.00	50	800
6(DF1)	12.50	400	800
7(DF2)	5.000	400	800
8(FW)	10.00	0	100
9(WHB)	80.00	50	300
10(CT2)	43.33	150	300

Expected output: -

To design water-reuse network for this problem and make a cost/benefit analysis of the selected water-reuse options. The solution of this problem is given in section B.2 of Appendix-B.

3.3 WATER MINIMIZATION IN STEAM GENERATION PLANT (PROBLEM 3.3)

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

Input Data: -

The Stream data is shown in the Table 3.3 given below.

Table 3.3. Stream Data for Water Minimization for Problem 3.3

Operation	$f_{i,in}$	$C_{i,in}^{\lim}$	$C_{i,out}^{\lim}$
i	t/h	ppm	ppm
1 (DW)	350	6.0	322.7
2 (E1)	360	6.4	15.6
3 (E2)	360	2.1	10.8
4 (SC)	60	20.0	207.0
5 (FW)	50	0.0	3.0

Expected output: -

To design water-reuse network for this problem and make a cost/benefit analysis of the selected water-reuse options. The solution of this problem is given in section B.3 of Appendix- B.

SOLUTION TECHNIQUE ADOPTED

In this Chapter the methodology, used for targeting and optimal designing of water network, is given. Graphical approach, based on Pinch Technology, is proposed for targeting and designing of some water system problems.

4.1 METHOD OF GRAPHICAL APPROACH

In this section the algorithm and flowchart of Graphical approach for targeting and designing of water network is proposed. The details of Graphical approach are discussed in Chapter-2 in section 2.4.

In the present work, three water system problems are targeted and designed by Graphical approach. These problems are stated in Chapter-3 and discussed in Appendix-A. The details of the solution for these problems are given in Appendix-B. Though most of the water system problems are not alike and need specialized treatment to solve, never the less an appropriate common frame work for their solution can be worked out as shown below:

4.1.1 Algorithm

To solve water system problems using Graphical approach, following steps should be followed.

4.1.1.1 Understand, and develop, the specifics of the process and the thesis

A clear understanding of the following thesis information is essential before carrying-out the subsequent data-extraction step.

Depending on the specifics of the case at hand, there can be any of a number of water-saving objectives.

It may not be feasible to analyze all the process units at a given plant site, for instance, because of great distances between them or a diversity of great distances between them or a diversity of contaminants involved. Conversely, examining a single process unit may be too restrictive, as there would be too few opportunities for water-reuse. Take into account the geography and chemistry of the processes to make the study more manageable. This guideline suggests looking at processes that are close together and chemically related.

Key contaminant is: 'any property that prevents direct reuse of a waste water stream', this might include temperature and /or acidity. Choose design concentrations-maximum allowable for sinks and minimum practical for sources. This may require input from experts in the relevant process technologies.

A utility is a water source, water demand, or unit operation whose water flow rate can be changed. For each utility, determine the maximum and minimum allowable flow rate, and, if possible, identify the fixed and variable costs associated with it. The fixed cost refers to the annualized standing charge or capital costs, and the variable cost represents the annualized operating costs. However, there is a caveat: fixed cost introduces complicated mixed-integer behavior into mathematical optimization.

There is not a hard-and-fast cutoff for determining whether a given stream has a sufficient flow rate to be considered useful in acting as a source or demand. On the other hand, it can be useful to have reasonable cutoff for data gathering purposes, so as to avoid streams, which the operators regard as having a minimal flow rates.

4.1.1.2 Extract the relevant data

It is necessary to determine flow rates and water quality requirements for all water users and processing steps. Possible sources for the process-related data needed for optimizing the water usage include the plant operators and filed process flow diagrams and process and instrumentation diagrams. Also needed will be the fresh water costs, as well as the limits on wastewater flow to an offsite facility or a body of water.

We apply the extracted data to develop water - use surveys and water - balance diagrams.

1. The water-use surveys are a spreadsheet containing of the gathered data. It contains detailed stream information in terms of flow rates and contaminant concentrations. The data should remain grouped according to the plant section.
2. The next step is to illustrate the survey in the form of water-balance diagrams. Each plant section studied should have its own water-balance diagram. Furthermore, each section can have a separate diagram for each water type, if combining all water types in one diagram becomes too complex.

4.1.1.3 Make an analysis of water sources and demands

Particularly during the preliminary analysis, limit the scope based on common sense. For instance, if the plant is on a large river and some of the process units are already employing river water whereas others are not, it seems likely that the river is too contaminated for the process units not already using its water, and it may be excluded from water-saving studies. Instead, concentrate on identifying opportunities available for other, more valuable water sources.

4.1.1.4 Conduct water-pinch analysis of the water-reuse options

Carryout the water-pinch analysis to determine optimum matches between sources and sinks using these steps:

Step 1: Develop mass problem table.

Step 2: Draw limiting concentration-composite curve.

Step 3: Develop water-reuse design network.

The first round of results will probably not be a practical design, as it represents an unconstrained solution. Identify pinches, examine the sensitivity plots, and relax constraints. Consider process modifications and regeneration options that may result in lower target.

4.1.1.5 Review the results of water-pinch analysis

Examine the resulting network design. It is usually necessary at this point to evaluate the design and determine which additional contaminants should be considered, which matches should be forbidden, and which matches (if any) should be forced. If some or all reuse proposals seem unsound, repeat steps 4.1.1.1 – 4.1.1.5 until a practical design has been evolved.

4.1.1.6 Make a cost/benefit analysis of the selected water-reuse options

Prepare an economic evaluation of the overall water-reuse proposal. Begin by creating a preliminary engineering design of the proposed water-using network. Then calculate the equipment and piping costs, including required retrofits to the existing facility. Analyze the direct and indirect economic benefits. Determine the payback period for each proposed reuse option.

It is important to keep in mind, and take credit for; the "double" cost savings involved in water reuse and waste water minimization.

4.1.2 Details of different steps encountered during targeting and design of water network

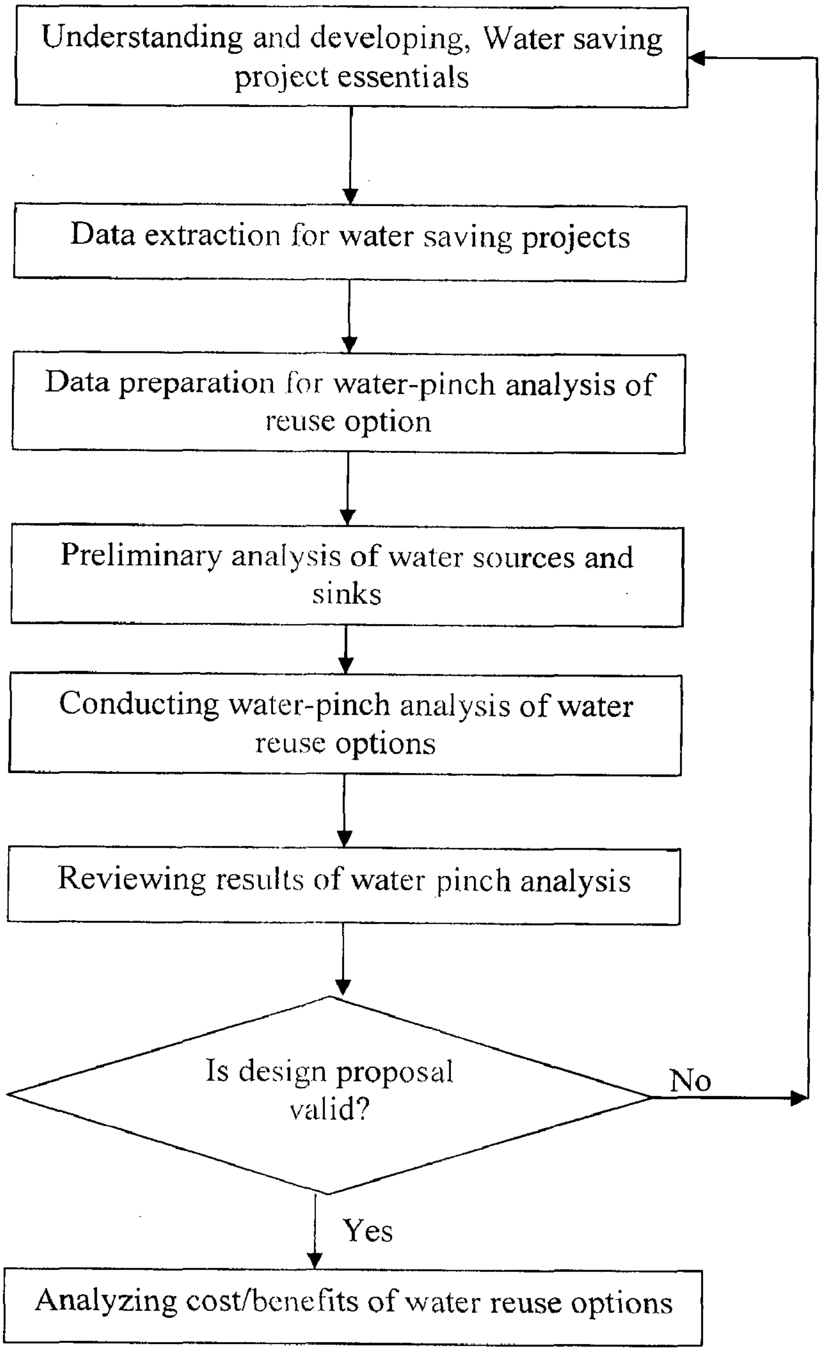


Figure 4.1. Flow chart of graphical approach for water network design

RESULTS AND DISCUSSIONS

This Chapter discusses the salient results obtained by solving three water system design problems of mass transfer (problem number 3.1 to 3.3). The stream input data and cost data for these problems are given in Table 3.1, Table 3.2, Table 3.3 and Table A.1. The description, of these problems, is provided in Appendix-A. These water system design problems are analysed and optimum design of water using network was developed by using Graphical approach discussed in Chapter-2. This technique is a new graphical tool for optimization of water system design network. The above technique is basically an extension of Pinch Technology (developed for heat exchange network) to mass exchange network. The optimum water-using network is a network of water using operations, which offers minimum total annual cost. The solution of water system design problems were divided into four phases: the targeting phase, the design phase, the modification phase and then optimum design phase. An algorithm was developed to carry out these tasks. The details of the algorithm are discussed in Chapter-4. Two computer programs (program A and program B) in MATLAB were developed to solve above problems and are given in Appendix-C with sample data files and results. The details of results obtained for all these problems are discussed in this chapter.

5.1 SALIENT RESULTS OF PROBLEM 3.1

In this problem, five water-using operations from Fig.A.1 are considered. The stream data and cost data are given in Table 3.1 and Table A.1. The whole problem is described in section A.1 of Appendix-A and the solution is given in section B.1 of Appendix- B. With these data given in Table 3.1 as input, the computer program A of Appendix- C computes following results in terms of targets:

1. The minimum fresh water flow rate = 26.53 t/h
2. The average pinch concentration = 15.6 ppm

5.1.1 Development of water design network

One water design network is developed for minimum flow rate of fresh water.

5.1.1.1 Design of Network for minimum fresh water flow rate

For above case, when the flow rate of fresh water stream is minimum, the average fresh water mass load of contaminant is 0.42 kg/h. The detail design of water network for these values is discussed in section B.1 of Appendix-B and shown in Fig.5.1.

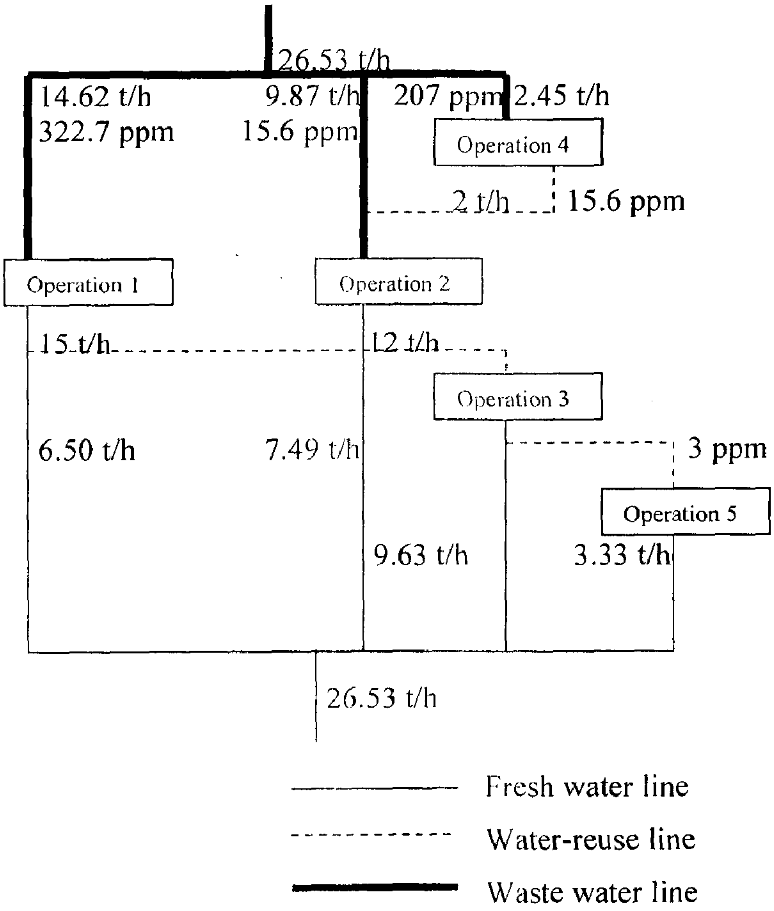


Fig.5.1. Water-reuse network for Problem 3.1

From Fig.5.1, we see water reuse:

a) Reuse of the boiler blow down as make up water for CTA.

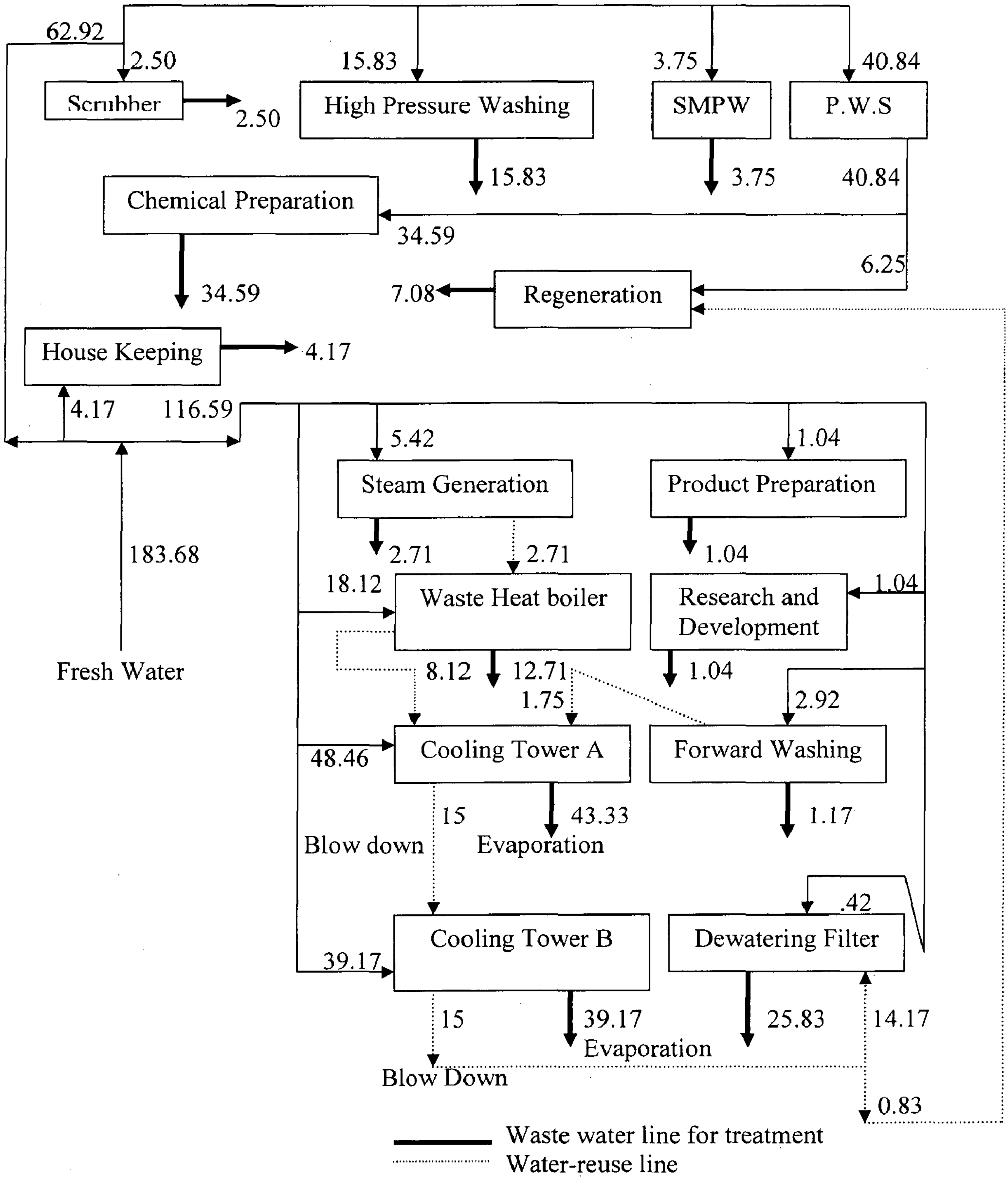
b) Reuse of steam condensate as boiler feed water.

c) Reuse of the blow down of the CTB as washing water in the dewatering filters.

d) Reuse of forward washing water as make up water to CTB.

e) Reuse of the blow down of CTB as make up water for CTA.

By using these reuse options, we prepare a final water-use network for Problem 3.1, which is discussed in Fig.B.3 and reproduced in Fig.5.2.



All data are in t/h

Fig.5.2. Final water-use network for Problem 3.1

5.1.2 Cost/benefit analysis

We prepare an economic evaluation of the over-all water-reuse proposal. The detail cost/benefit analysis of the selected water-reuse proposal is discussed in section B.1 of Appendix-B and shown in Table 5.1. Table 5.1 has following salient features:

Table 5.1. Cost/benefit analysis of water-reuse options for Problem 3.1

Option	Water reuse	Needed Retrofit, equipments	Capital Investment, Rs	Water savings, t/h	Annual benefit, Rs	Payback time, months
1	FWW as CTA make upwater	Buffer vessel pump, piping	6,760	1.75	11,810	7
2	CTB Blow down as washing water for DF	Piping, control valves, small filter	1,040	8.1	54,640	0.23
3	CTA blow down as CTB makeup water	Existing piping	0	12.57	84,790	0
4	Boiler blowdown as CTA make up water	Pump, control valves, piping, Heat-exchanger	44,980	8.12	54,780	10
5	Steam condensate as boiler feed water	Existing piping	0	2.71	18,280	0
6	CTB blowdown as filter washing water	Piping	1,240	0.83	5,600	2.7
	SUMMARY		54,020	34.08	2,29,900	2.8

From Table 5.1 we see the following results:

1. Total amount of freshwater savings = 34.08 t/h
2. Total annual benefit = Rs.2,29,900
3. Total reduction in waste water generation = 42.58 t/h
4. Total pay-back time = 2.8 months

5.2 SALIENT RESULTS OF PROBLEM 3.2

In this problem, ten water-using operation from Fig.A.2. are considered. The stream data and cost data are given in Table 3.2 and Table A.1. The whole problem is described in section A.2 of Appendix-A and the solution is given in section B.2 of Appendix- B. With these data given in Table 3.2 as input, the computer program A of Appendix- C computes following results in terms of targets:

1. The minimum fresh water flow rate = 166.42 t/h
2. The average pinch concentration = 100 ppm

5.2.1 Development of water design network

One water design network is developed for minimum flow rate of fresh water.

5.2.1.1 Design of Network for minimum fresh water flow rate

For above case, when the flow rate of fresh water stream is minimum, the average fresh water mass load of contaminant is 16.64 kg/h. The detail design of water network for these values is discussed in section B.2 of Appendix-B and shown in Fig.5.3.

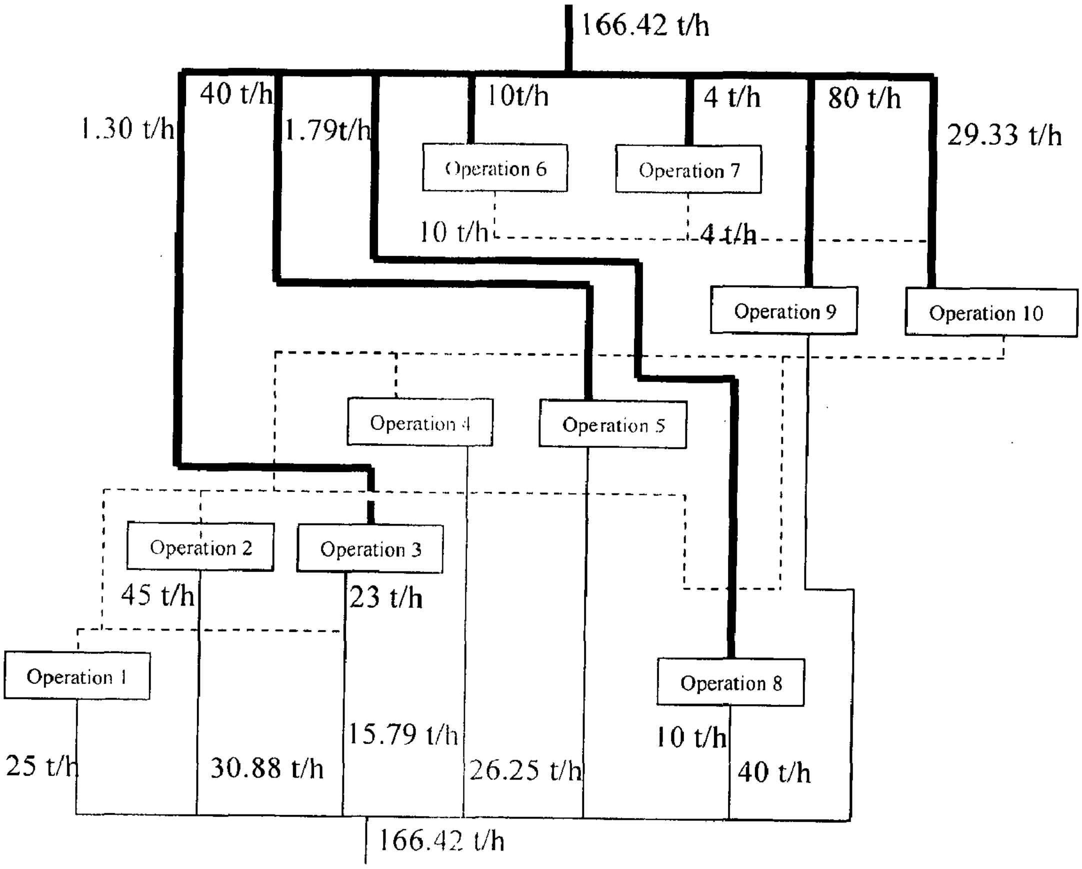


Fig.5.3. Water-reuse network for Problem 3.2

From Fig.5.3, we see water reuse:

a) Water reuse from the blow-down of the economizers as make up water for cooling tower 1.

b) Reuse of forward washing water as make up water to cooling tower 1.

c) Reuse of the blow down of cooling tower 1 as washing water in the dewatering filters 1& 2.

d) Reuse of the boiler blow down as make up water for economizers 1, 2 &3.

e) Reuse of steam condensate as boiler feed water.

By using these reuse options, we prepare a final water-use network for Problem 3.2, which is discussed in Fig.B.6 and reproduced in Fig.5.4.

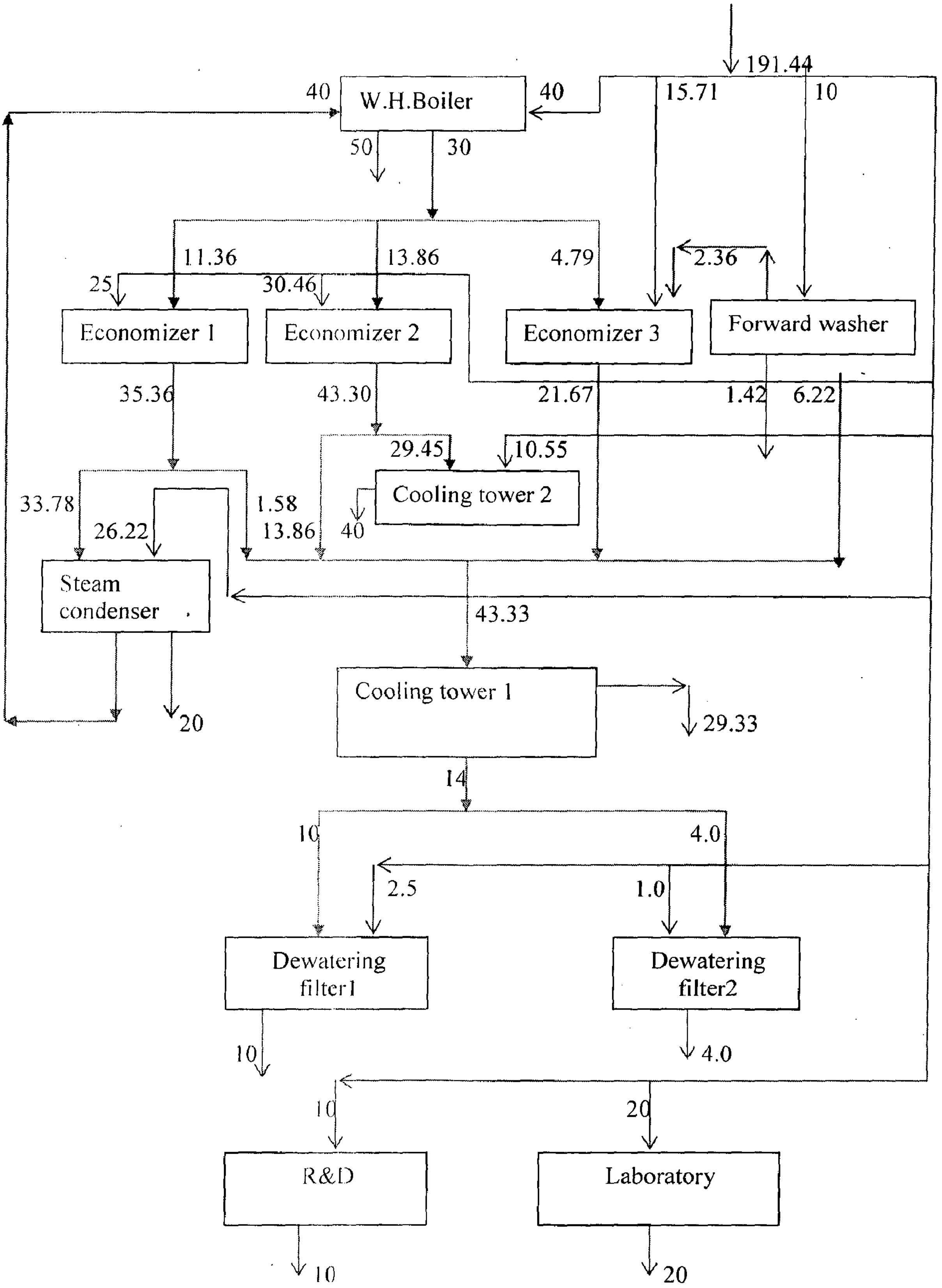


Fig.5.4. Final water-use network for Problem 3.2

5.2.2 Cost/benefit analysis

We prepare an economic evaluation of the over-all water-reuse proposal. The detail cost/benefit analysis of the selected water-reuse proposal is discussed in section B.2 of Appendix-B and shown in Table 5.2. Table 5.2 has following salient features:

Table 5.2. Cost/benefit analysis of water reuse options for Problem 3.2

Option	Water reuse	Needed Retrofit, equipments	Capital Investment, Rs	Water savings, t/h	Annual benefit, Rs	Payback time, months
1	FWW as CT1 make up water	Buffer vessel pump, piping	6,760	6.22	41,957	1.933
2	CT1 Blow down as washing water for DF	Piping, control valves, small filter	1,040	14	94,436	0.132
3	Economizers blow down as CT1 makeup water	Existing piping	1240	66.56	4,48,573	0.033
4	Boiler blowdown as economizers make up water	Pump,control valves,piping, Heat-exchanger	44,980	30	2,02,363	2.66
5	Steam condensate as boiler feed water	Existing piping	0	40	2,69,818	0
	SUMMARY		54,020	156.78	10,57,147	4.758

From Table 5.2 we see the following results:

1. Total amount of freshwater savings = 156.78 t/h
2. Total annual benefit = Rs.10,57,147
3. Total reduction in waste water generation = 126.42 t/h
4. Total pay-back time = 4.758 months

5.3 SALIENT RESULTS OF PROBLEM 3.3

In this problem, five water-using operations from Fig. A.3. are considered. The stream data and cost data are given in Table 3.3 and Table A.1. The whole problem is described in section A.3 of Appendix-A and the solution is given in section B.3 of Appendix- B. With these data given in Table 3.3 as input, the computer program A of Appendix- C computes following results in terms of targets:

1. The minimum fresh water flow rate = 637.83 t/h
2. The average pinch concentration = 15.6 ppm

5.3.1 Development of water design network

One water design network is developed for minimum flow rate of fresh water.

5.3.1.1 Design of Network for minimum fresh water flow rate

For above case, when the flow rate of fresh water stream is minimum, the average fresh water mass load of contaminant is 9.95 kg/h. The detail design of water network for these values is discussed in section B.3 of Appendix-B and shown in Fig.5.5.

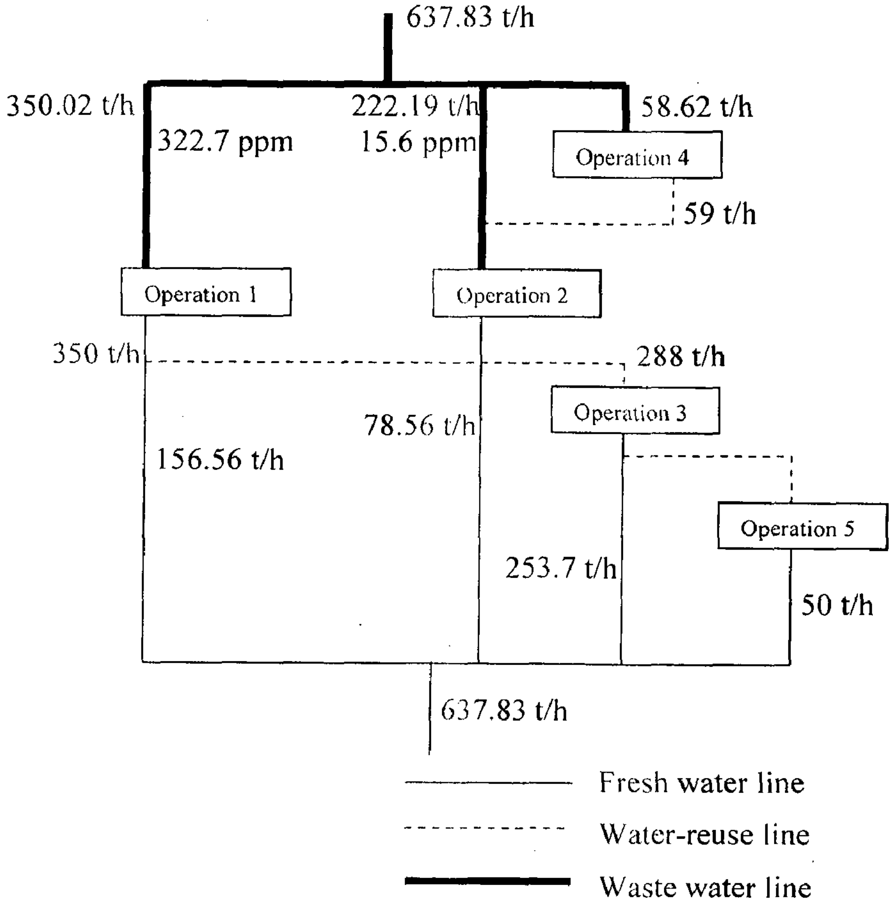


Fig.5.5. Water-reuse network for Problem 3.3

From Fig.5.5, we see water reuse:

a. Water reuse from the blow-down of the economizer 2 as make up water for economizer 1.

b. Reuse of forward washing water as make up water to economizer 2.

c. Reuse of the blow down of economizer 2 as washing water in the dewatering filters.

d. Reuse of the boiler blow down as make up water for economizer 1.

e. Reuse of steam condensate as boiler feed water.

By using these reuse options, we prepare a final water-use network for Problem 3.3, which is discussed in Fig.B.9 and reproduced in Fig.5.6.

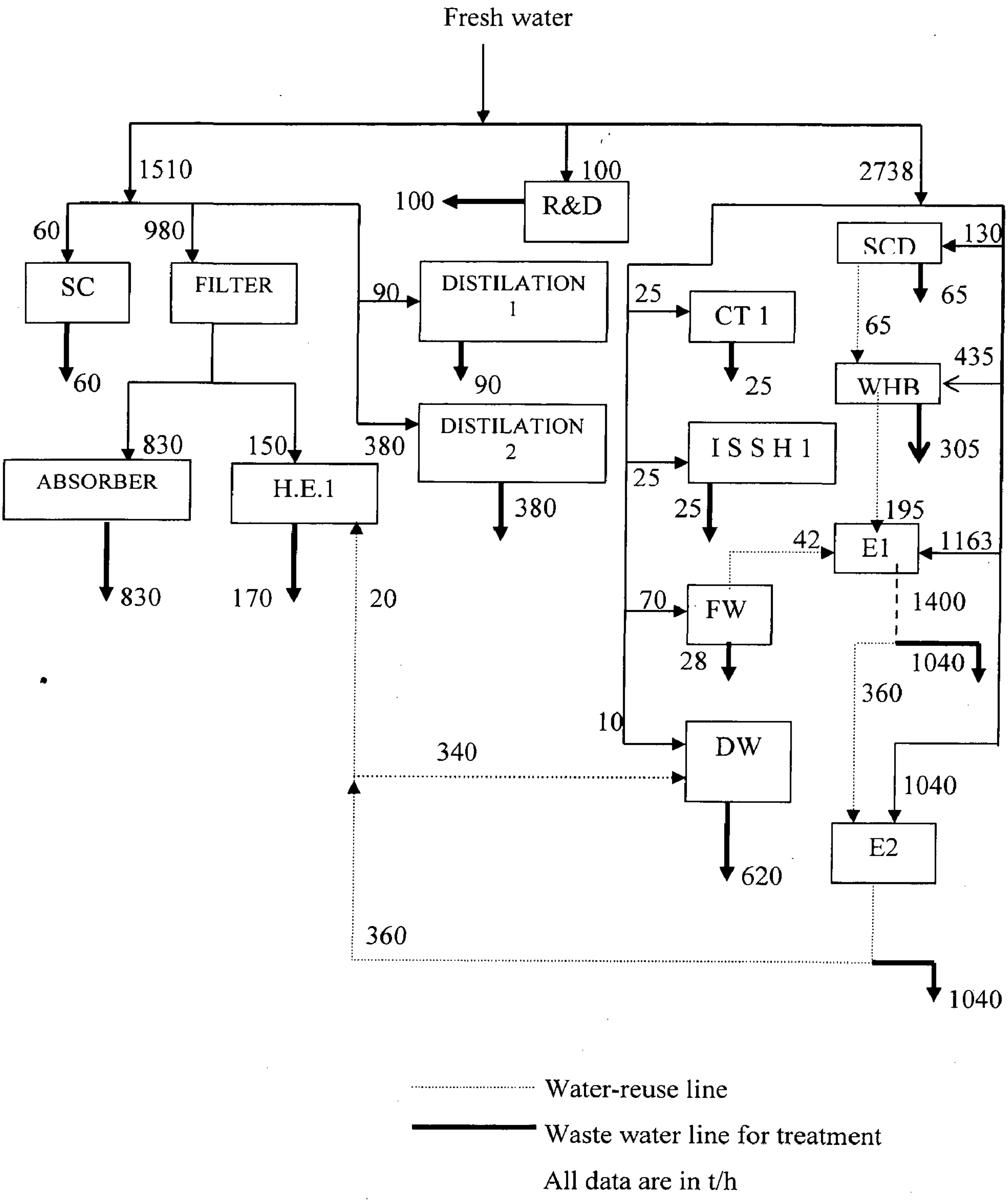


Fig.5.6. Final water-use network for Problem 3.3

5.3.2 Cost/benefit analysis

We prepare an economic evaluation of the over-all water-reuse proposal. The detail cost/benefit analysis of the selected water-reuse proposal is discussed in section B.3 of Appendix-B and shown in Table 5.3. Table 5.3 has following salient features:

Table 5.3. Cost/benefit analysis of water-reuse options for Problem 3.3

Option	Water reuse	Needed Retrofit, equipements	Capital Investment, Rs	Water savings, t/h	Annual benefit, Rs	Payback time, months
1	FWW as E1 make up water	Buffer vessel pump, piping	6,550	42	11,340	7
2	E2 Blow down as washing water for DF	Piping, control valves, small filter	1,000	340	91,800	0.13
3	E1 blow down as E2 makeup water	Existing piping	0	360	97,260	0
4	Boiler blowdown as E1 make up water	Pump,control valves,piping, Heat-exchanger	43,640	195	52,650	10
5	Steam condensate as boiler feed water	Existing piping	0	65	17,550	0
6	E2 blow down as filter washing water	Piping	1,200	20	5,700	5.3
	SUMMARY		52,410	1,022	2,76,300	22.43

From Table 5.3 we see the following results:

1. Total amount of freshwater savings = 1022 t/h
2. Total annual benefit = Rs. 2,76,300
3. Total reduction in waste water generation = 1022 t/h
4. Total pay-back time = 22.43 months

CONCLUSIONS AND RECOMMENDATIONS

Three water system problems were solved by graphical method proposed by Wang and Smith to get the optimum water network. These problems were targeted by two computer programs and then designed. These programs (Program A and Program B) were written in MATLAB and were run in Pentium-IV, 933 MHz machine. From all this systematic study and results discussed in Chapter-5, following conclusions have been drawn.

6.1 CONCLUSIONS

1. 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.
    i. For the first problem, the targeted value of minimum freshwater flow rate is 26.53 t/h. With the help of water-reuse design network, we see a reduction in fresh water consumption from 230.42 to 183.68 t/h (a 20 % decrease) and an associated reduction in wastewater generation from 154.99 to 112.41 t/h (a 28 % decrease) with an annual benefit of Rs. 2,29,900.
    ii. For the second problem, the targeted value of minimum freshwater flow rate is 166.42 t/h. With the help of water-reuse design network, we see a reduction in fresh water consumption from 384.36 to 191.44 t/h (a 50 % decrease) and an associated reduction in wastewater generation from 314.36 to 187.94 t/h (a 40 % decrease) with an annual benefit of Rs. 10,57,147.
    iii. For the third problem, the targeted value of minimum freshwater flow rate is 637.83 t/h. With the help of water-reuse design network, we see a reduction in fresh water consumption from 5430 to 4348 t/h (a 20 % decrease) and an associated reduction in wastewater generation from 3720 to 2698 t/h (a 28 % decrease) with an annual benefit of Rs. 2,76,300.
2. Currently published water pinch theory is suited to analyzing water which is used in a process as a utility; it is less suitable for situations where water is

intrinsic to the technology of the process, for example in a hydrometallurgical process.

3. 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.

6.2 RECOMMENDATIONS

On the basis of present work, following recommendations are made for further study:

1) Further work is needed to extend the water pinch analysis methodology to account for chemically reacting solutes and aqueous reagents.
2) Techniques for the early identification of the applicability of water pinch need to be developed.
3) Techniques need to be developed to reduce the time and effort required to gather the data needed for a water pinch analysis.
4) The use of water pinch analysis as a tool for co-regulation should be explored.
5) The energy efficiency of a process has a significant impact on its water use for cooling and the concomitant generation of saline effluents.

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PROBLEM DESCRIPTIONS

PROBLEMS TO BE HANDLED

A.1 Description of Problem 3.1

A water balance diagram for Problem 3.1 is demonstrated in Fig.A.1.

This diagram constitutes a systematic way for making an audit of current water use and wastewater generations.

The Fig.A.1 shows three general areas of water use, including process uses, utility uses and other uses.

The aim is to find the network configuration that will minimize the overall demand for freshwater (and thus minimize wastewater generation) at minimum total annual cost.

The stream data is given in section 3.1 of Chapter-3.

The cost data for this problem is taken from Coulson et al., (1993) and is shown in Table A.1.

Table A.1. Cost Data for Water Minimization Problem

Needed Retrofit, equipments	Capital Investment, Rs.
Buffer vessel Pump, piping	6,760
Piping, control valves, small filter	1,040
Existing piping	0
Pump, control valves, piping	44,980
Heat-exchanger	0
Piping	1,240
Water cost/kg	0.85

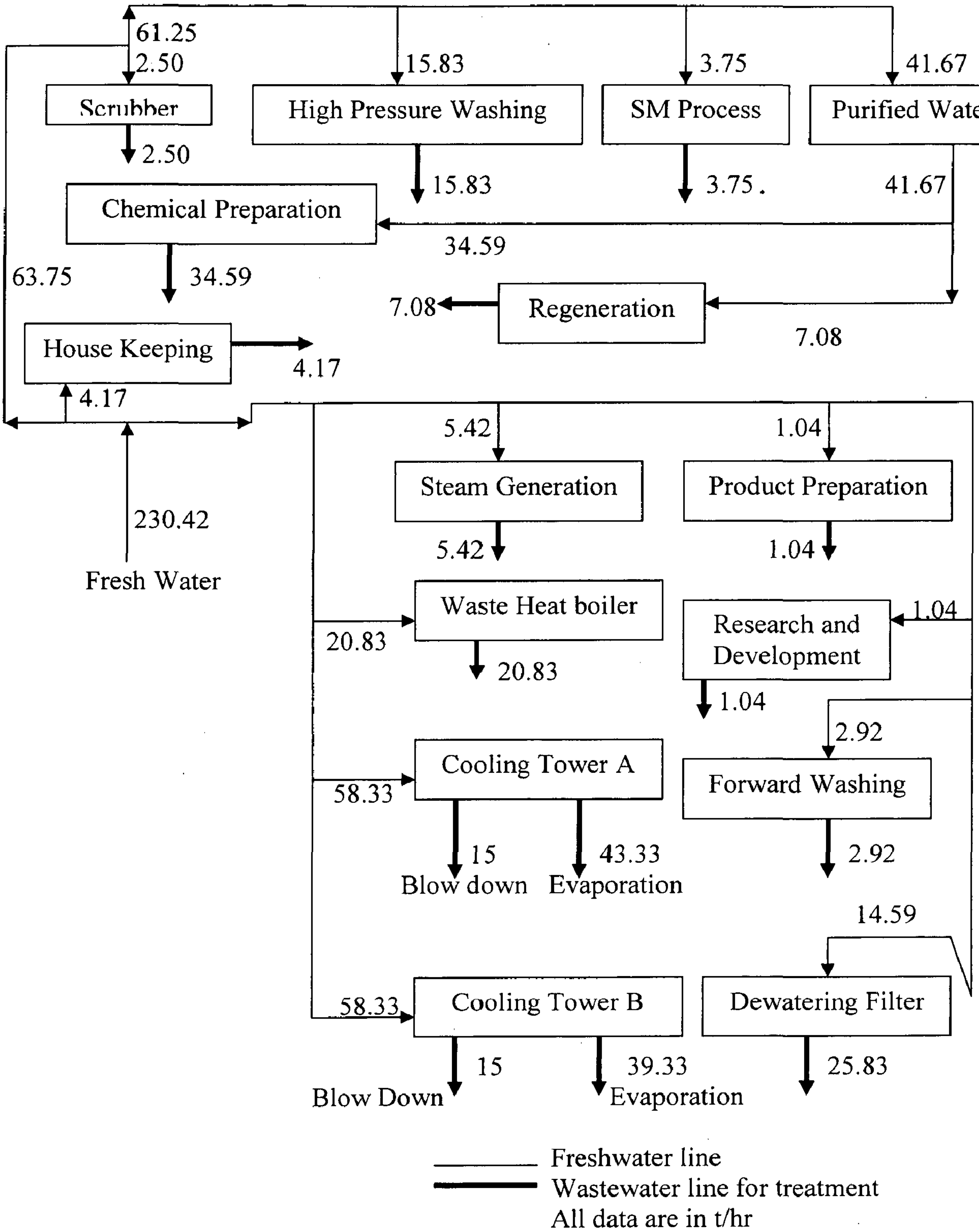


Fig.A.1.Initial water-use network for Problem 3.1

A.2 Description of Problem 3.2

A water balance diagram for Problem 3.2 is demonstrated in Fig.A.2.

This diagram constitutes a systematic way for making an audit of current water use and wastewater generations.

The Fig.A.2 shows three general areas of water use, including process uses, utility uses and other uses.

The aim is to find the network configuration that will minimize the overall demand for freshwater (and thus minimize wastewater generation) at minimum total annual cost.

The stream data is given in section 3.2 of Chapter-3.

The cost data for this problem is taken from Coulson et al., (1993) and was shown in Table A.1.

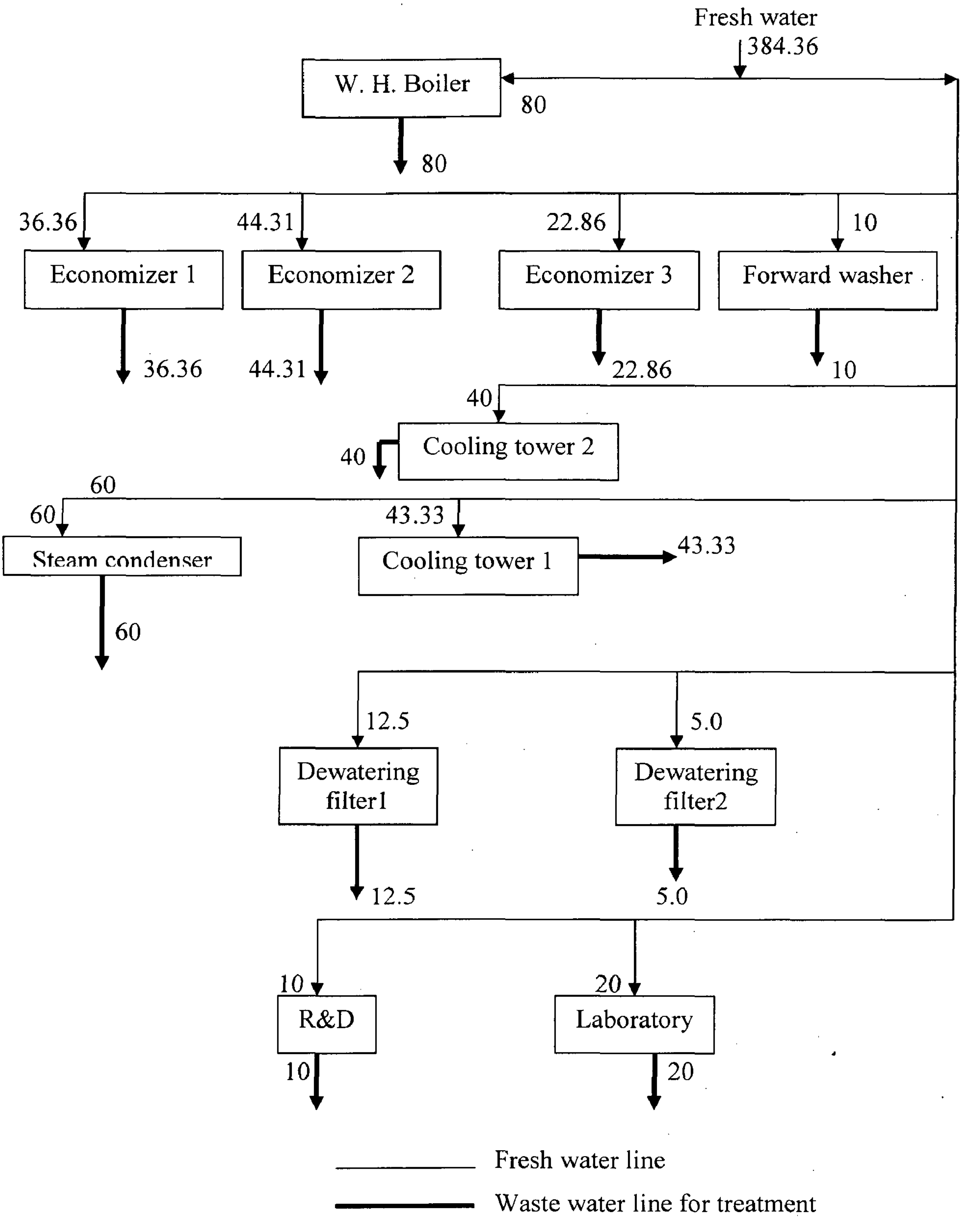


Fig.A.2. Initial water-use network for Problem 3.2

A.3 Description of Problem 3.3

A water balance diagram for Problem 3.3 is demonstrated in Fig.A.3.

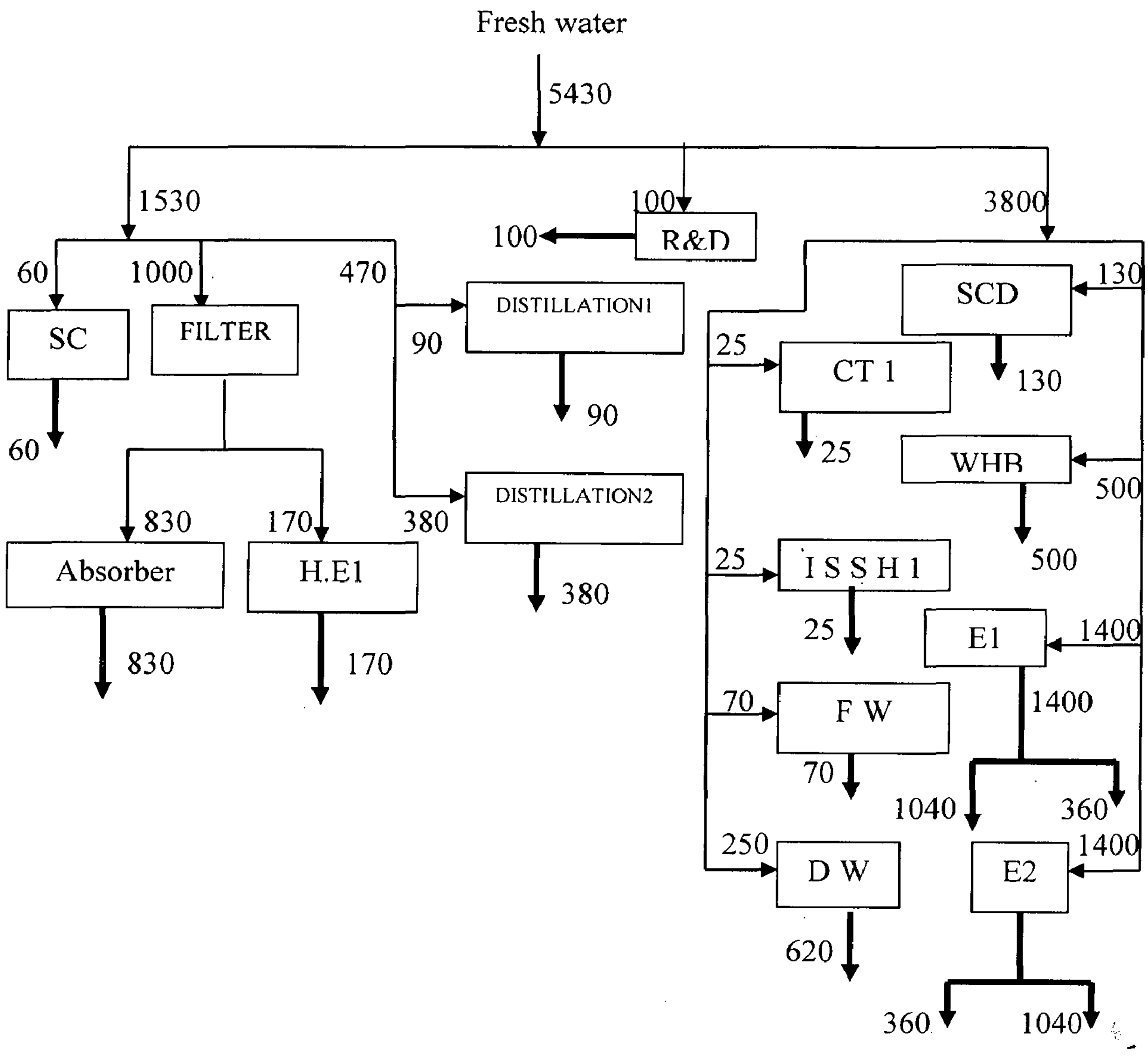
This diagram constitutes a systematic way for making an audit of current water use and wastewater generations.

The Fig.A.3 shows three general areas of water use, including process uses, utility uses and other uses.

The aim is to find the network configuration that will minimize the overall demand for freshwater (and thus minimize wastewater generation) at minimum total annual cost.

The stream data is given in section 3.3 of Chapter-3.

The cost data for this problem is taken from Coulson et al., (1993) and was shown in Table A.1.



Fresh water line

Wastewater line for treatment

All data are in t/hr

Fig.A.3.Initial water-use network for Problem 3.3

SAMPLE CALCULATIONS

B.1 SAMPLE CALCULATION OF PROBLEM 3.1

Calculation for Single Water Source

The stream data for this problem is shown in Table 3.1.

Calculation for Minimum Freshwater Flow Rate

Step 1: Calculation of mass load of contaminant

The mass load of contaminant corresponding to each process stream can be calculated as:

$$\Delta m_{i,tot} = f_{i,in} \times \left[C_{i,in}^{\lim} - C_{i,out}^{\lim}\right] \qquad \text{...(B.1)}$$

The limiting process data is shown in Table B.1.

Table B.1. Limiting Process Data for Problem 3.1

Operation	$f_{i,in}$	$f_{i,out}$	$C_{i,in}^{\lim}$	$C_{i,out}^{\lim}$	$\Delta m_{i,tot}$
i	t/h	t/h	ppm	ppm	kg/h
1 (DW)	14.59	25.83	6.0	322.7	4.62
2 (CTA)	58.33	15	6.4	15.6	0.14
3 (CTB)	58.33	15	2.1	10.8	0.13
4 (SC)	2.50	2.5	20.0	207.0	0.47
5 (FW)	1.75	1.75	0.0	3.0	0.01

Step 2: Calculation for Mass Problem Table

In the MPT an arrow represents any process operation. The tail of each arrow corresponds to the limiting inlet concentration of the water stream, $C_{in,\max,i}$, while the head represents the limiting outlet concentration, $C_{out,\max,i}$. We begin by establishing a series of mass intervals in such a way, which along each interval there are always the same operations present. The interval extremes correspond to the heads and tails of these arrows. The number of concentration intervals, N_{int} , can be related to the number of operations, N_0, through the following expression:

$$N_{\text{int}} \leq 2N_0 - 1 \qquad \text{.... (B.2)}$$

With the equality applying in cases where no two heads or tails coincide. Intervals numbering, concentrations and operations representation constitutes the first three columns of the MPT.

For the remaining columns, simple calculations are required. The fourth column indicates the sum of the limiting water flow rates, $\sum f_i$, of the operations present in each interval, while the fifth tells us the amount of mass transferred in each interval. For interval j, this is calculated by

$$\Delta m_j = \left(\sum f_i\right)_j \times \left[C_j - C_{j-1}\right] \qquad \text{.... (B.3)}$$

With

$$C_{j=0} = \min\left\{C_{in.\max,i}\right\} \qquad \text{.... (B.4)}$$

Cumulative mass transferred is presented in the next column and given by:

$$\Delta m_{cumulative,j} = \Delta m_1 + \Delta m_2 + \Delta m_3 + \ldots\ldots\ldots\ldots + \Delta m_j = \sum \Delta m_j \qquad \text{....(B.5)}$$

The MPT can only be applied for a single water source. For it to be capable of solving the entire mass exchange duty, the concentration in the contaminant, C_{ws}, must verify the following condition:

$$C_{ws} \le C_{j=0} \qquad \text{.... (B.6)}$$

Minimum water flow rate that can be used, f_{ws}, while respecting the constraints of the problem, is determined from the values in the seventh column, by

$$f_{ws} = \max\left(\frac{\Delta m_{cumulative,j}}{C_j - C_{ws}}\right) \qquad \text{....(B.7)}$$

The mass problem table is calculated by the above method and shown in Table B.2.

Table B.2. Mass Problem Table for Problem 3.1

Concentration	Mass load	Cumulative mass load	Flow rate
ppm	kg/h	kg/h	t/h
0		0	0
	0.01		
2.1		0.01	3.33
	0.02		
3		0.03	7.81
	0.04		
6		0.07	11.38
	0.01		
6.4		0.08	12.51
	0.2		
10.8		0.28	25.66
	0.14		
15.6		0.42	26.53
	0.06		
20		0.48	24.23
	3.2		
207		3.69	17.82
	1.69		
322.7		5.38	16.67

Step 3: Plot concentration-composite curve

The concentration composite curve and water supply line are plotted as given below.

Plot each water using operation head to toe on a graph of concentration versus mass load of contaminant transferred with in the operation. Divide the y-axis into concentration intervals by drawing horizontal lines at the limiting inlet and outlet concentrations for each water using operation. Sum the mass load with in each concentration interval, created from the set of inlet and outlet concentrations, to give the composite curve. Remove the original lines representing each operation, to yield concentration-composite curve. Plot a water-supply line, which begins at the origin. Its position is established by rotating the line counter-clockwise about the origin until it becomes tangent to the composite curve.

The limiting concentration composite curve and water supply line is shown in Fig.B.1.

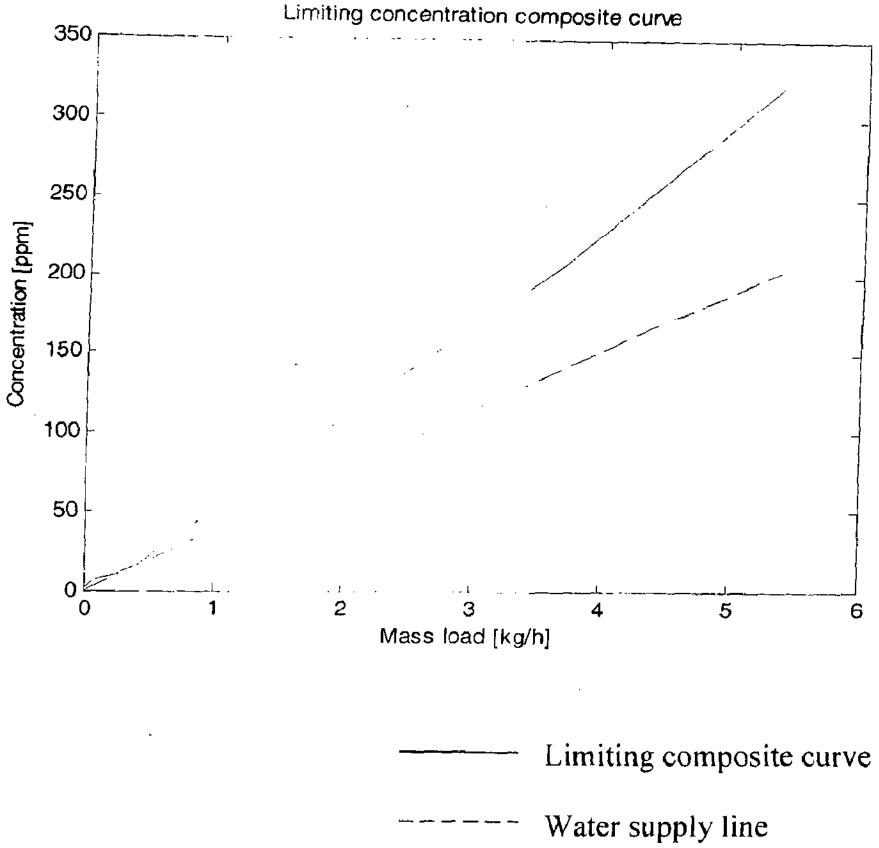


Fig.B.1. Limiting concentration curve for Problem 3.1

From Fig.B.1, we have the following results:

1. Minimum flow rate of freshwater = 26.53 t/h
2. Average pinch concentration = 15.6 ppm
3. Mass load of contaminant = 0.42 kg/h

These results imply that the plant can meet all of its water needs by using fresh water up to a concentration of 15.6 ppm. Above this pinch concentration, the plant does not need any fresh water, and can reuse existing water sources to satisfy its water demands.

Step 4: Water-reuse design network

With the help of pinch concentration, we can develop water-reuse design network. The water-reuse design network is shown in Fig.B.2.

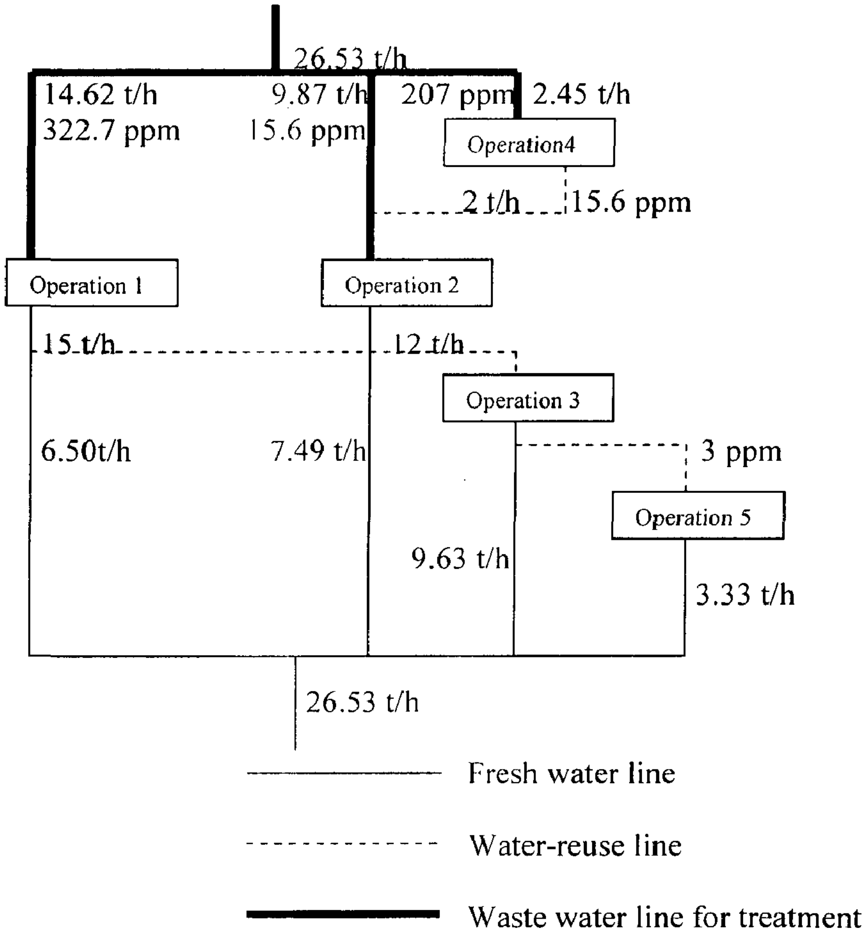


Fig.B.2. Water-reuse diagram for Problem 3.1

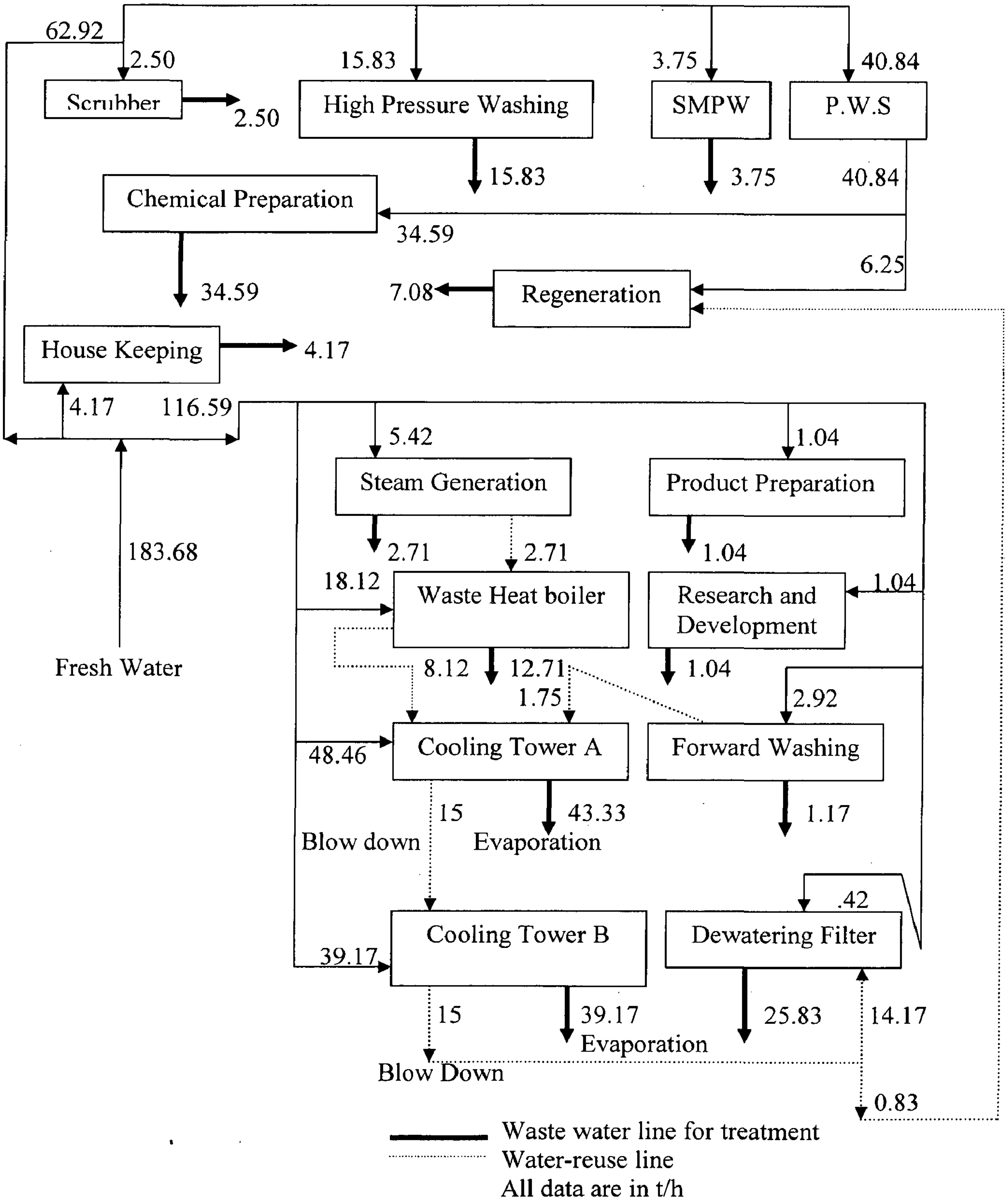
From Fig.B.2, we see water reuse:

a) Reuse of the boiler blow down as make up water for CTA
b) Reuse of steam condensate as boiler feed water
c) Reuse of the blow down of the CTB as washing water in the dewatering filters.

In actuality, numerous properties of a water stream may render it unfit for reuse. We reassess each option suggested by the water-pinch synthesis, as well as other reuses made available by the addition of several water sources not included in the initial analysis:

a) Reuse of the boiler blow down as make up water for CTA
b) Reuse of steam condensate as boiler feed water
c) Reuse of the blow down of the CTB as washing water in the dewatering filters2.
d) Reuse of forward washing water as make up water to CTB
e) Reuse of the blow down of CTB as make up water for CTA

By using these reuse options, we prepare a final water-use network for Problem 3.1, which is discussed in Fig.B.3.



FigureB.3. Final water-use network for Problem 3.1

Fig.B.3 illustrates the water use and reuse by Units. Comparing Fig.B.3 with Fig.A.1 before applying water-pinch technology, we see a reduction in fresh water consumptions from 230.42 to 183.68 t/h (a 20 % decrease) and associated reduction in wastewater generation from 154.99 to 112.41 t/h (a 28 % decrease).

Step 5: Calculation for cost/benefit analysis:

The cost data for this problem is shown in Table A.1.The annual benefit and payback time is calculated as shown in Table B.3.

Table B.3. Cost/benefit analysis of water-reuse options for Problem 3.1

Option	Water reuse	Needed Retrofit, equipments	Capital Investment, Rs	Water savings, t/h	Annual benefit, Rs	Payback time, months
1	FWW as CTA make upwater	Buffer vessel pump, piping	6,760	1.75	11,810	7
2	CTB Blow down as washing water for DF	Piping, control valves, small filter	1,040	8.1	54,640	0.23
3	CTA blow down as CTB makeup water	Existing piping	0	12.57	84,790	0
4	Boiler blow down as CTA make up water	Pump, control valves, piping, Heat-exchanger	44,980	8.12	54,780	10
5	Steam condensate as boiler feed water	Existing piping	0	2.71	18,280	0
6	CTB blow down as filter washing water	Piping	1,240	0.83	5,600	2.7
	SUMMARY		54,020	34.08	2,29,900	2.8

Table B.3 shows the equipment needed, capital investment, fresh water savings, and payback period for the six water reuse modifications for Problem 3.1. The overall water-reuse proposal is attractive. It requires a capital investment of Rs.54,020, saves 34.08 t/h of fresh water and generates an annual benefit of Rs.2,29,900, corresponding to a payback time of only 2.8 months.

B.2 SAMPLE CALCULATION OF PROBLEM 3.2

Calculation for Single Water Source

The stream data for this problem is shown in Table 3.2.

Calculation for Minimum Freshwater Flow Rate

Step 1: The mass load of contaminant corresponding to each process stream can be calculated as above and shown in Table B.4.

Table B.4. Limiting Process Data for Problem 3.2

Operation	$f_{i,m}$	$C_{i,in}^{\lim}$	$C_{i,out}^{\lim}$	$\Delta m_{i,tot}$
i	t/h	ppm	ppm	kg/h
1 (EC1)	36.36	25	80	2
2(EC2)	44.31	25	90	2.88
3(EC3)	22.86	25	200	4
4(SC)	60.00	50	100	3
5(CT1)	40.00	50	800	30
6(DF1)	12.50	400	800	5
7(DF2)	5.000	400	800	2
8(FW)	10.00	0	100	1
9(WHB)	80.00	50	300	20
10(CT2)	43.33	150	300	6.50

Step 2: Calculation for Mass Problem Table

The mass problem table is calculated as shown in section B.1 of appendix-B and shown in Table B.5.

Table B.5 Mass problem table for problem 3.2

Concentration	Mass load	Cumulative mass load	Flow rate
ppm	kg/h	kg/h	t/h
0		0	0
	0.25		
25		0.25	10
	2.86		
50		3.11	62.13
	8.83		
80		11.93	149.17
	2.58		
90		14.51	161.25
	2.13		
100		16.64	166.42
	7.15		
150		23.79	158.61
	9.32		
200		33.11	165.53
	16.33		
300		49.44	164.8
	4		
400		53.44	133.6
	23		
800		76.44	95.55

Step 3: Plot concentration-composite curve

The limiting concentration composite curve and water supply line is plotted as discussed in section B.1 of Appendix-B and shown in Fig.B.4.

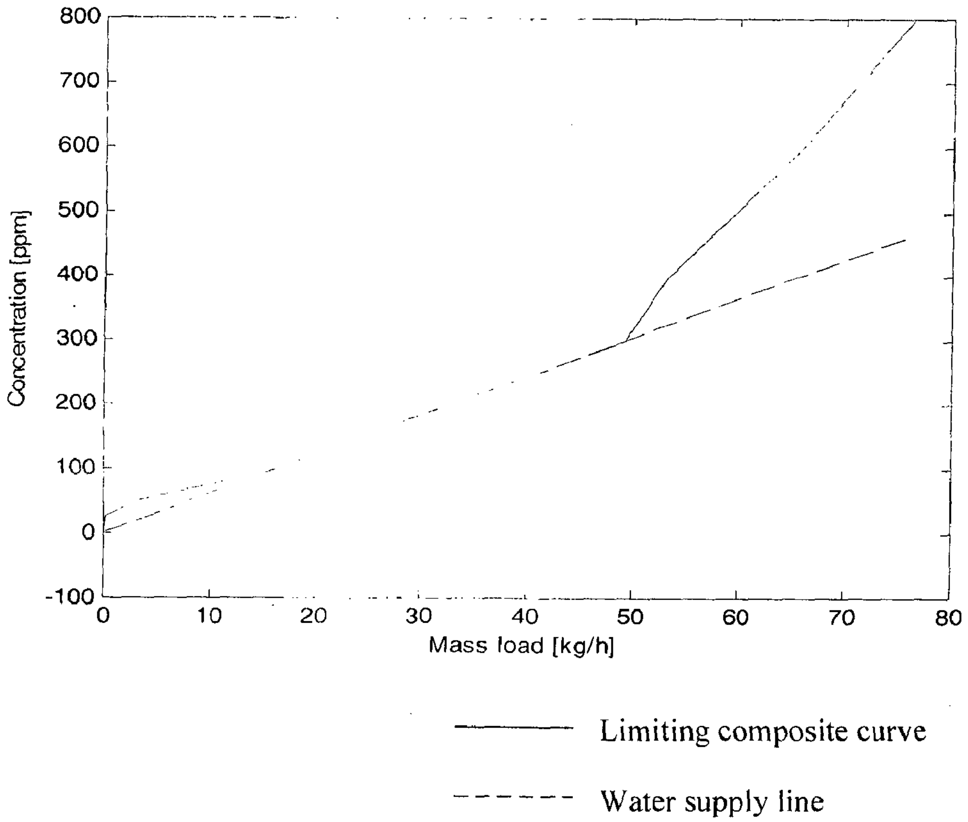


Fig.B.4. Limiting concentration curve for Problem 3.2

From Fig.B.4, we have the following results:

1. Minimum flow rate of freshwater = 166.42 t/h
2. Average pinch concentration = 100 ppm
3. Mass load of contaminant = 16.64 kg/h

These results imply that the plant can meet all of its water needs by using fresh water up to a concentration of 100 ppm. Above this pinch concentration, the plant does not need any fresh water, and can reuse existing water sources to satisfy its water demands.

Step 4: Water-reuse design network

The water-reuse design network is discussed in section B.1 of Appendix-B and shown in Fig.B.5.

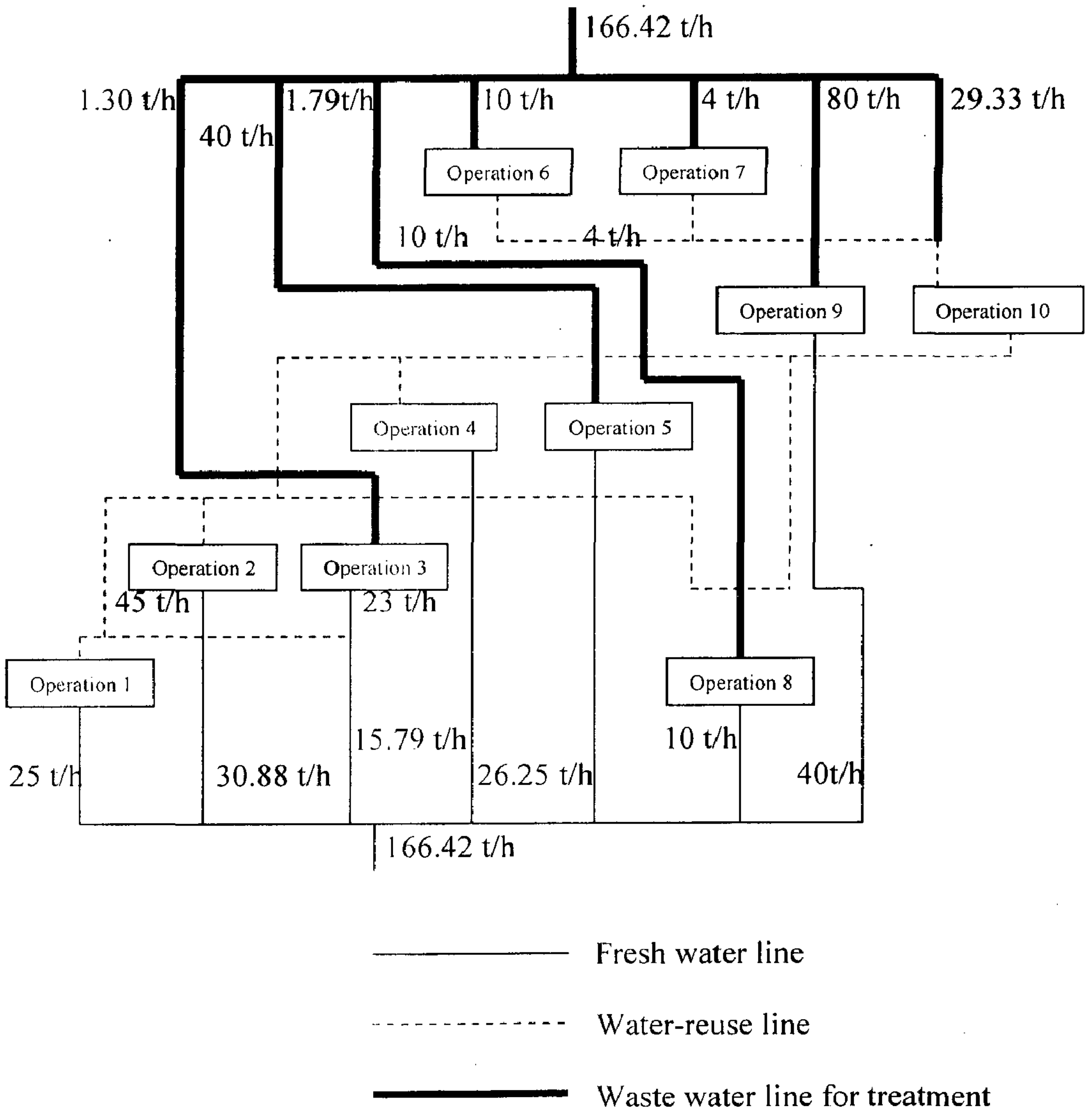


Fig.B.5. Water–reuse network for Problem 3.2

From Fig.B.5, we see water reuse:

a) Water reuse from the blow-down of the economizers as make up water for cooling tower 1.

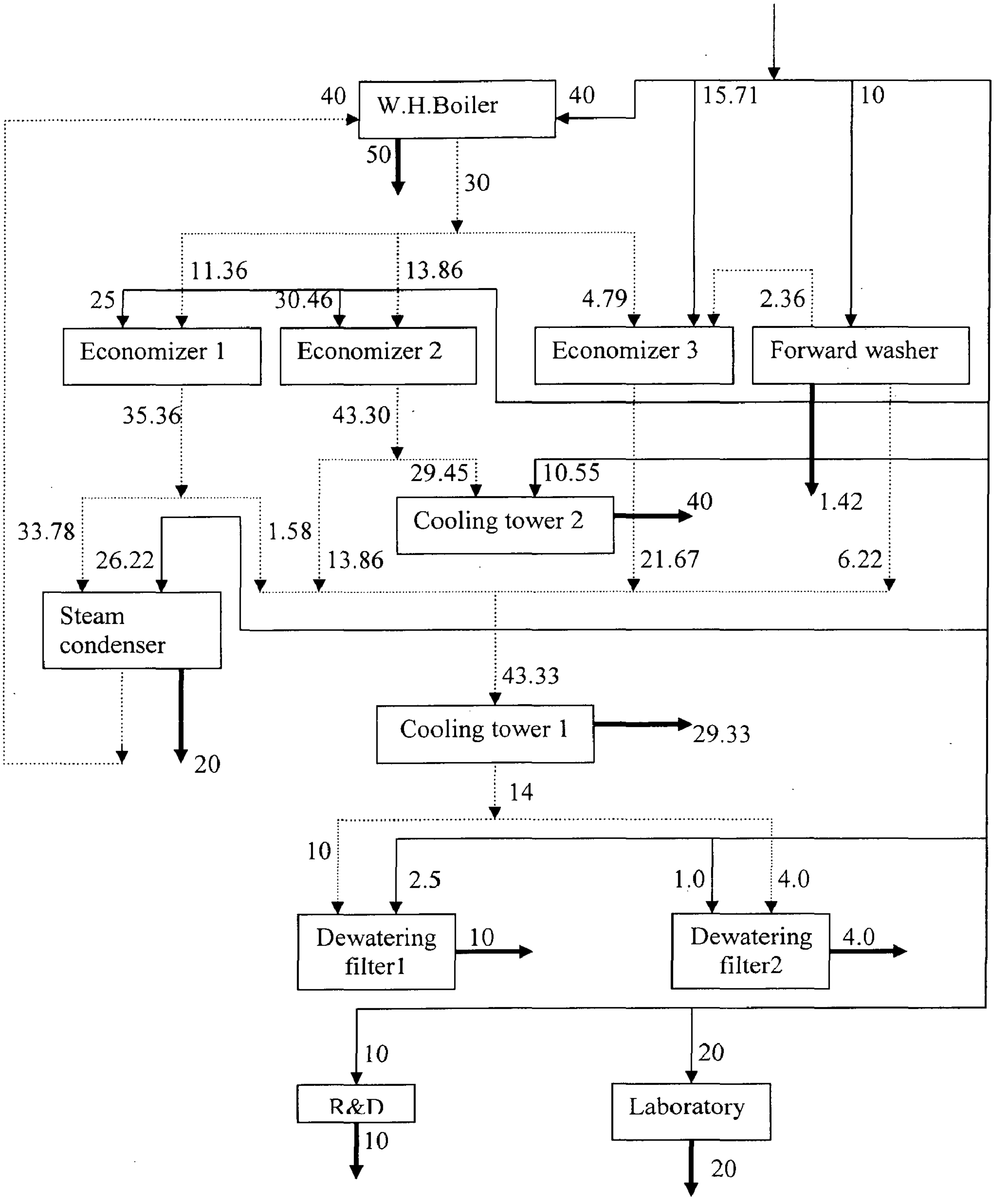
b) Reuse of forward washing water as make up water to cooling tower 1.

c) Reuse of the blow down of cooling tower 1 as washing water in the dewatering filters 1& 2.

d) Reuse of the boiler blow down as make up water for economizers 1, 2 & 3.

e) Reuse of steam condensate as boiler feed water.

By using these reuse options, we prepare a final water-use network for Problem 3.2, which is discussed in Fig.B.6.



Water-reuse line

Wastewater line for treatment

All data are in t/h

Figure B.6. Final water-use network for Problem 3.2

Fig.B.6 illustrates the water use and reuse by unit. Comparing Fig.B.6 with Fig.A.2 before applying water-pinch technology. We see a reduction in fresh water consumptions from 384.36 to 191.44 t/h (a 50 % decrease) and associated reduction in wastewater generation from 314.36 to 187.94 t/h (a 40 % decrease).

Step 5: Calculation for cost/benefit analysis:

The cost data for this problem is shown in Table A.1.The annual benefit and payback time is calculated as shown in Table B.6.

Table B.6. Cost/benefit analysis of water reuse options for Problem 3.2

Option	Water reuse	Needed Retrofit, equipments	Capital Investment, Rs	Water savings, t/h	Annual benefit, Rs	Payback time, months
1	FWW as CT1 make up water	Buffer vessel pump, piping	6,760	6.22	41,957	1.933
2	CT1 Blow down as washing water for DF	Piping, control valves, small filter	1,040	14	94,436	0.132
3	Economizers blow down as CT1 makeup water	Existing piping	1240	66.56	4,48,573	0.033
4	Boiler blowdown as economizers make up water	Pump, control valves, piping, Heat-exchanger	44,980	30	2,02,363	2.66
5	Steam condensate as boiler feed water	Existing piping	0	40	2,69,818	0
	SUMMARY		54,020	156.78	10,57,147	4.758

Table B.6 shows the equipment needed, capital investment, fresh water savings, and payback period for the five water reuse modifications for Problem 3.2. The overall water-reuse proposal is attractive. It requires a capital investment of Rs.54,020, saves 156.78 t/h of fresh water and generates an annual benefit of Rs.10,57,147, corresponding to a payback time of only 4.758 months.

B.3 SAMPLE CALCULATION OF PROBLEM 3.3

Calculation for Single Water Source

The stream data for this problem is shown in Table 3.3.

Calculation for Minimum Freshwater Flow Rate

Step 1: The mass load of contaminant corresponding to each process stream can be calculated as shown in Section B.1 of Appendix-B. The limiting process data is shown in Table B.7.

Table B.7. Limiting Process Data for Problem 3.3

Operation	$f_{i,in}$	$C_{i,in}^{\lim}$	$C_{i,out}^{\lim}$	$\Delta m_{i,tot}$
i	t/h	ppm	ppm	kg/h
1 (DW)	350	6.0	322.7	4.62
2 (E1)	360	6.4	15.6	0.14
3 (E2)	360	2.1	10.8	0.13
4 (SC)	60	20.0	207.0	0.47
5 (FW)	50	0.0	3.0	0.01

Step 2: Calculation for Mass Problem Table

The mass problem table is calculated as shown in section B.1 of appendix-B and shown in Table B.5.

Table B.8. Mass problem table for problem 3.3

Concentration	Mass load	Cumulative mass load	Flow rate
ppm	kg/h	kg/h	t/h
0		0	0
	0.11		
2.1		0.11	50
	0.37		
3		0.47	157.93
	1.08		
6		1.55	258.85
	0.28		
6.4		1.84	287.03
	4.71		
10.8		6.54	605.85
	3.41		
15.6		9.95	637.83
	1.54		
20		11.49	574.51
	76.67		
207		88.16	425.91
	40.5		
322.7		128.66	398.7

Step 3: Plot concentration-composite curve

The limiting concentration composite curve and water supply line is plotted as discussed in section B.1 of Appendix-B and shown in Fig.B.7.

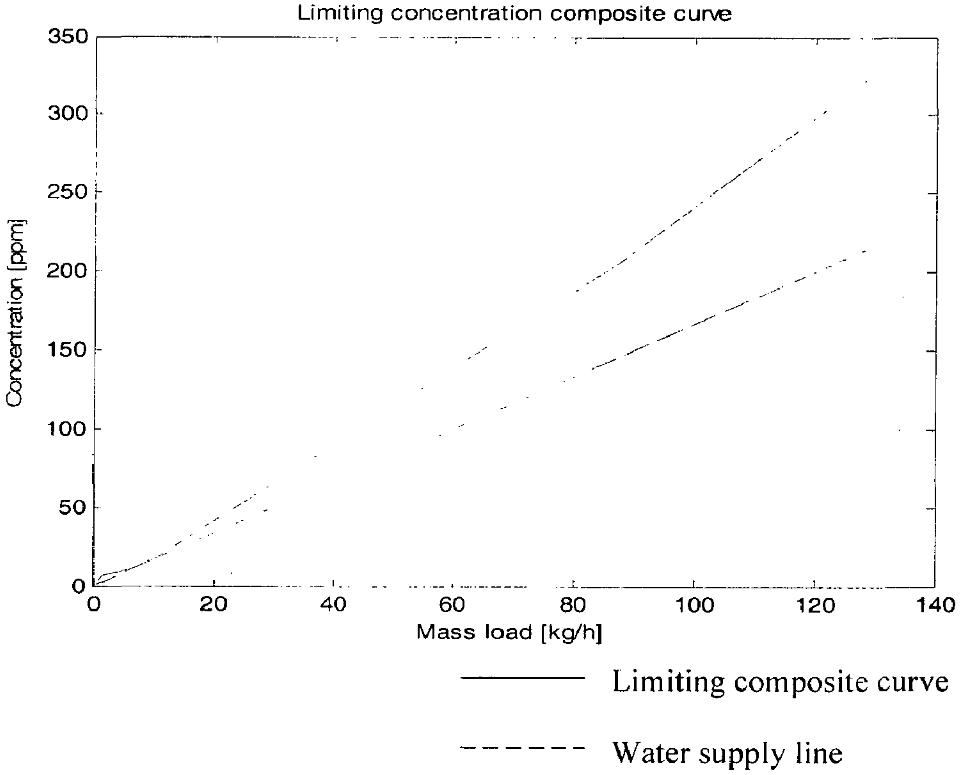


Fig.B.7. Limiting concentration curve for Problem 3.3

From Fig.B.7, we have the following results:

1. Minimum flow rate of freshwater = 637.83 t/h
2. Average pinch concentration = 15.6 ppm
3. Mass load of contaminant = 9.95 kg/h

These results imply that the plant can meet all of its water needs by using fresh water up to a concentration of 15.6 ppm. Above this pinch concentration, the plant does not need any fresh water, and can reuse existing water sources to satisfy its water demands.

Step 4: Water-reuse design network

The water-reuse design network is discussed in section B.1 of Appendix-B and shown in Fig.B.8.

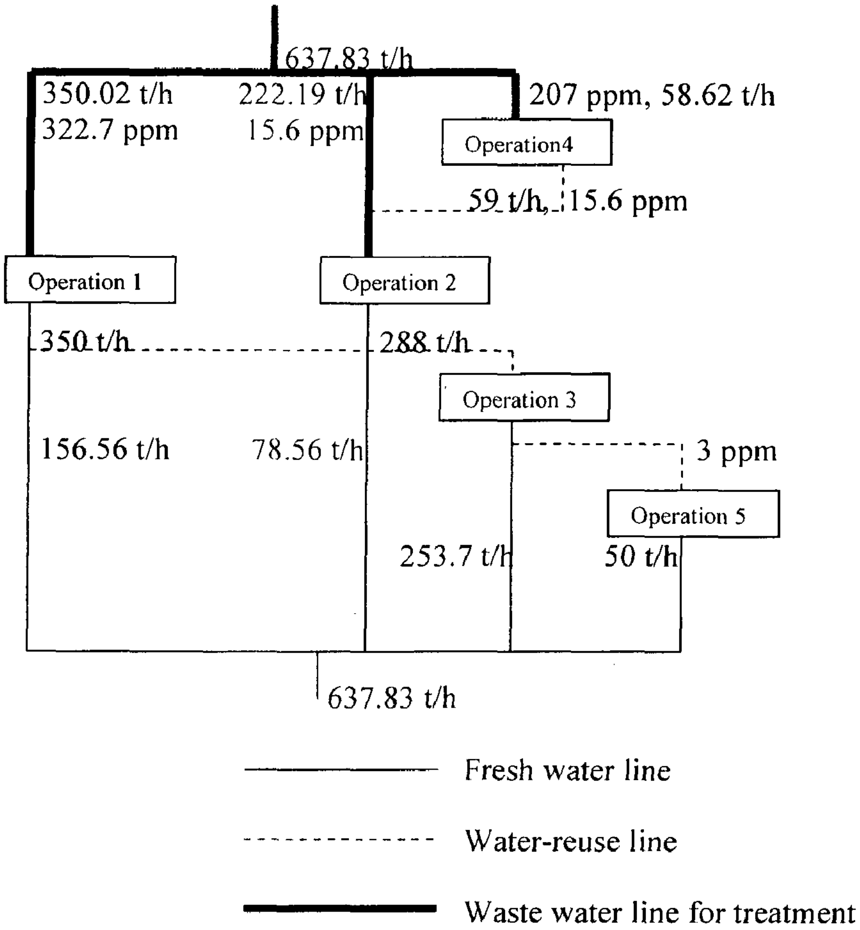


Fig.B.8. Water-reuse network for Problem 3.3

From Fig.B.8, we see water reuse:

a. Water reuse from the blow-down of the economizer 2 as make up water for economizer 1.
b. Reuse of forward washing water as make up water to economizer 2.
c. Reuse of the blow down of economizer 2 as washing water in the dewatering filters.
d. Reuse of the boiler blow down as make up water for economizer 1.
e. Reuse of steam condensate as boiler feed water.

By using these reuse options, we prepare a final water-use network for Problem 3.3, which is discussed in Fig.B.9.

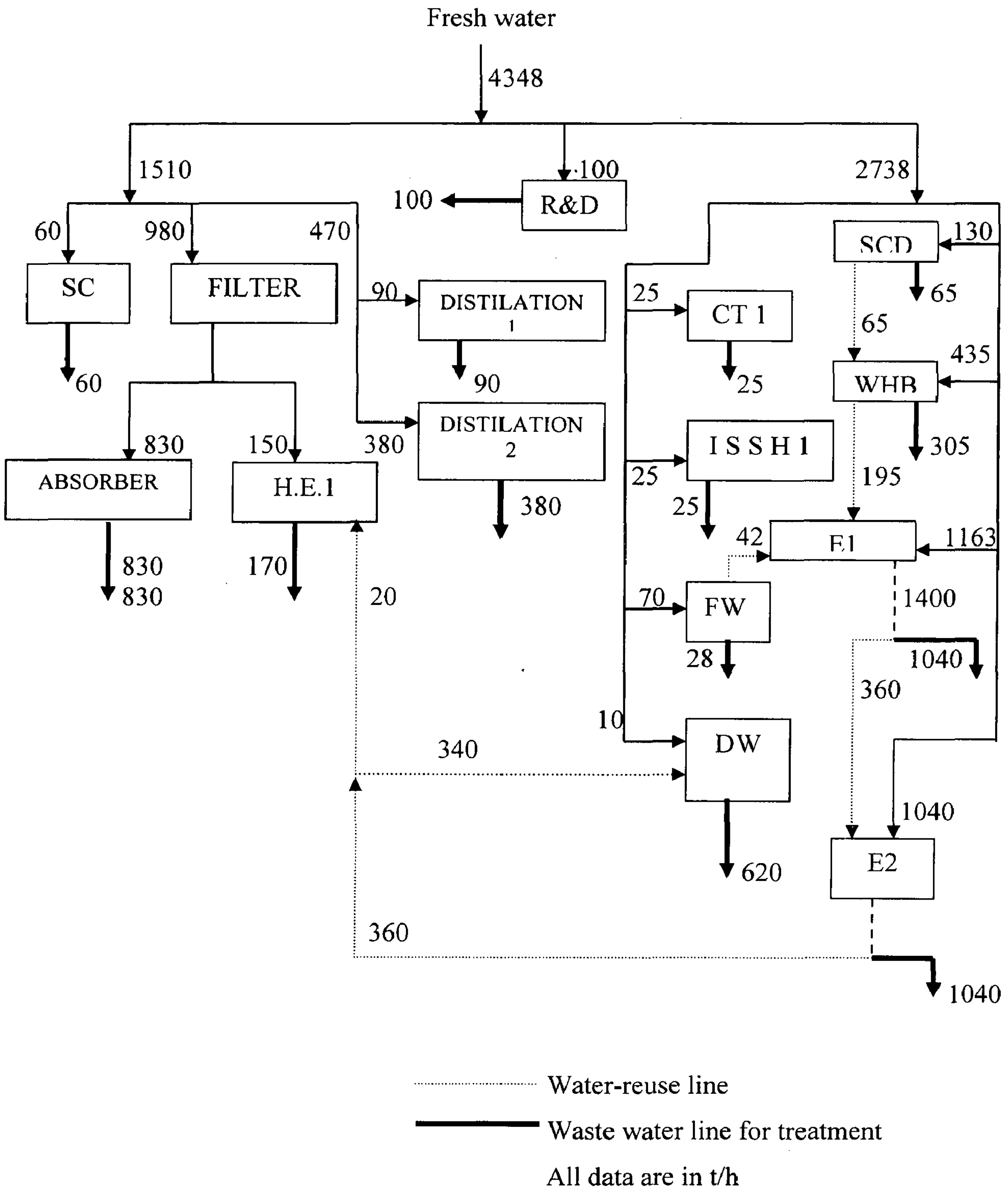


Fig.B.9. Final water-use network for Problem 3.3

Fig.B.9 illustrates the water use and reuse by Unit. Comparing Fig.B.9 with Fig.A.3 before applying water-pinch technology, we see a reduction in fresh water consumptions from 5430 to 4348 t/h (a 20 % decrease) and associated reduction in wastewater generation from 3720 to 2698 t/h (a 28 % decrease).

Step 5: Calculation for cost/benefit analysis:

The cost data for this problem is shown in Table A.1.The annual benefit and payback time is calculated as shown in Table B.9.

Table B.9. Cost/benefit analysis of water reuse options for Problem 3.3

Option	Water reuse	Needed Retrofit, equipments	Capital Investment, Rs	Water savings, t/h	Annual benefit, Rs	Payback time, months
1	FWW as E1 make up water	Buffer vessel pump, piping	6,550	42	11,340	7
2	E2 Blow down as washing water for DF	Piping, control valves, small filter	1,000	340	91,800	0.13
3	E1 blow down as E2 makeup water	Existing piping	0	360	97,260	0
4	Boiler blowdown as E1 make up water	Pump, control valves, piping, Heat-exchanger	43,640	195	52,650	10
5	Steam condensate as boiler feed water	Existing piping	0	65	17,550	0
6	E2 blow down as filter washing water	Piping	1,200	20	5,700	5.3
	SUMMARY		52,410	1,022	2,76,300	22.43

Table B.9 shows the equipment needed, capital investment, fresh water savings, and payback period for the six water reuse modifications for Problem 3.3. The overall water-reuse proposal is attractive. It requires a capital investment of Rs.52,410, saves 1022 t/h of fresh water and generates an annual benefit of Rs.2,76,300 corresponding to a payback time of only 22.43 months.

MODIFICATIONS FOR UREA PLANT
(PROBLEM 3.1):

1. From Fig.B.2 we see reuse directly from cooling tower B to cooling tower A. The blow down from cooling tower B is lower in flow rate as well as higher in conductivity and calcium concentration. However, we also see that suspended solids may become a problem due to the concentration restriction for the make up water to cooling tower B. In practice; we can solve this problem by including a small filter to remove suspended solids from the blow down of cooling tower A, prior to its reuse as make up water to cooling tower B.
2. Fig.B.2 suggests the reuse of 1.75 t/h of forward washing water in cooling tower B. However, let us consider reuse of the forward washing water to cooling tower A instead, as we have already assigned a water reuse from cooling tower A to cooling tower B. We see that the conductivity of the forward washing water is greater than that allowed for make up water to cooling tower A. However, this difference in water quality is significant because of the associated dilution of the forward washing water by far greater flow rate of the make up water. The relatively clean forward washing water and the relatively dirty backwashing water are currently combined in a neutralization vessel and sent to waste water treatment. We can instead reroute the forward washing water to a new storage vessel. The retrofit design includes the vessel, piping; and pumps to transport the water from the storage vessel to cooling tower A at a cost of Rs.6,760. We see a fresh water savings and waste water reduction of 1.75 t/h to give an annual benefit of Rs.11,810. The payback period for this reuse is 7 months.
3. Fig.B.2 suggests reusing 8.1 t/h of blow down from cooling tower B in the dewatering filters. The required retrofit includes piping, control valves, and a filter to remove suspended solids from the blow down stream of cooling tower B prior to its reuse as washing water for dewatering filters. The capital investment is approximately Rs.1,040, for water savings of 8.1 t/h. The annual benefit of Rs.54,640 corresponds to a payback period of merely 0.23 months.
4. A water source listed in table, but not included in the water-pinch analysis is the boiler blow down of 8.12 t/h. This reuse of the boiler blow down is possible due to the dilution effect of the make up water. The main difficulty in

reusing the boiler blow down is its high temperature. We need to include a heat exchanger to cool the boiler blow down leaving the waste heat boiler prior to using it as make up water to cooling tower A. The increased capital investment is Rs.44,980, for savings of 8.12 t/h of fresh water. The annual benefit of Rs.54,780 gives a payback period of 10 months.

5. Another water source listed in table but not included in the water-pinch analysis is 2.71 t/h of steam condensate. At the plant, piping is currently in place for the reuse of steam condensate.

MODIFICATIONS FOR RECTISOLE PLANT (PROBLEM 3.2):

1. The amount is 66.56 t/h. However, we also see that suspended solids may become a problem due to the concentration restriction for the make up water to cooling tower 1.In practice; we can solve this problem by including a small filter to remove suspended solids from the blow down of economizers, prior to its reuse as make up water to cooling tower 1.
2. Fig.B.5 suggests the reuse of 6.22 t/h of forward washing water in cooling tower 1. The relatively clean forward washing water and the relatively dirty backwashing water are currently combined in a neutralization vessel and sent to waste water treatment. We can instead reroute the forward washing water to a new storage vessel. The retrofit design includes the vessel, piping; and pumps to transport the water from the storage vessel to cooling tower 1 at a cost of Rs.6,760.We see a fresh water savings and waste water reduction of 6.22 t/h to give an annual benefit of Rs.41,957. The payback period for this reuse is 1.933 months.
3. Fig.B.5 suggests reusing 14 t/h of blow down from cooling tower 1 in the dewatering filters. The required retrofit includes piping, control valves, and a filter to remove suspended solids from the blow down stream of cooling tower 2 prior to its reuse as washing water for dewatering filters. The capital investment is approximately Rs.1,040, for water savings of 14 t/h. The annual benefit of Rs. 94,436 corresponds to a payback period of merely 0.132 months.
4. A water source listed in table, but not included in the water-pinch analysis is the boiler blow down of 30 t/h. The main difficulty in reusing the boiler

blow down is its high temperature. We need to include a heat exchanger to cool the boiler blow down leaving the waste heat boiler prior to using it as make up water to cooling tower A. The increased capital investment is Rs.44,980, for savings of 8.12 t/h of fresh water. The annual benefit of Rs.2,02,363 gives a payback period of 2.66 months.

5. Another water source listed in table but not included in the water-pinch analysis is 40 t/h of steam condensate. At the plant, piping is currently in place for the reuse of steam condensate.

MODIFICATIONS FOR STEAM GENERATION PLANT (PROBLEM 3.3):

1. However, we also see that suspended solids may become a problem due to the concentration restriction for the make up water to economizer 2.In practice; we can solve this problem by including a small filter to remove suspended solids from the blow down of economizer 1, prior to its reuse as make up water to economizer 2.
2. Fig.B.8 suggests the reuse of 42 t/h of forward washing water in economizer 2. However, let us consider reuse of the forward washing water to economizer 1 instead, as we have already assigned a water reuse from economizer 1 to economizer 2. Table compares the important stream properties when considering such reuse of the forward washing water. We see that the conductivity of the forward washing water is greater than that allowed for make up water to economizer 1. However, this difference in water quality is significant because of the associated dilution of the forward washing water by far greater flow rate of the make up water. The relatively clean forward washing water and the relatively dirty backwashing water are currently combined in a neutralization vessel and sent to waste water treatment. We can instead reroute the forward washing water to a new storage vessel. The retrofit design includes the vessel, piping; and pumps to transport the water from the storage vessel to economizer 1 at a cost of Rs.6,760. We see a fresh water savings and wastewater reduction of 42 t/h to give an annual benefit of Rs.11,340. The payback period for this reuse is 7 months.
3. Fig.B.8 suggests reusing 340 t/h of blow down from economizer 2 in the dewatering filters. The required retrofit includes piping, control valves, and a

filter to remove suspended solids from the blow down stream of economizer 2 prior to its reuse as washing water for dewatering filters. The capital investment is approximately Rs.1,000, for water savings of 340 t/h. the annual benefit of Rs. 91,800 corresponds to a payback period of merely 0.13 months.

4. A water source listed in table, but not included in the water-pinch analysis is the boiler blow down of 195 t/h. This reuse of the boiler blow down is possible due to the dilution effect of the make up water. The main difficulty in reusing the boiler blow down is its high temperature. We need to include a heat exchanger to cool the boiler blow down leaving the waste heat boiler prior to using it as make up water to economizer 1. The increased capital investment is Rs.43,640, for savings of 195 t/h of fresh water. The annual benefit of Rs.52,650 gives a payback period of 10 months.
5. Another water source listed in table but not included in the water-pinch analysis is 65 t/h of steam condensate. At the plant, piping is currently in place for the reuse of steam condensate.

COMPUTER PROGRAMME

DETAILS OF THE COMPUTER PROGRAMME

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 A.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.
2	Program B.MB	This program gives the total amount of the capital investment, Total amount of water saving, Total annual benefit. It takes also the help of the different input files to solve different problems.

Program A.MB & Program B.MB are interconnected with each other.

Input files And Output Files:

The comments for the order of entering the data in input file are given in main programs. Input and output files for both Program A.MB and Program B.MB are attached with programs.

Program A.MB :

Program for find out the limiting fresh water requirement

```
%scriptfileWaterPinch.
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');
format bank
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';
Sol_table=[Cj F0 dm dM FWs];
fprintf('Mass Problem Table For Given Problem\n');
fprintf('-------------------------------------\n');
fprintf('     Cj(ppm)         fi(t/h)        dmj(kg/h)
dmc(kg/h)       fws(t/h)\n');
disp(Sol_table);
A=max(FWs);
fprintf('The minimum water flow rate in t/h=%6.2f',A);
```

The input data for problem 3.1 is given in Table C.2.

Table C.2. Sample Input Data of ProgramA.MB for Problem 3.1

Operation	$f_{i,in}$	$C_{i,in}^{\lim}$	$C_{i,out}^{\lim}$
i	t/h	ppm	ppm
1	14.59	6.0	322.7
2	58.33	6.4	15.6
3	58.33	2.1	10.8
4	2.50	20.0	207.0
5	1.75	0.0	3.0

The output data of Mass problem calculation for problem 3.1 is given in Table C.3.

Table C.3. Sample Output Results of Program A.MB for Problem 3.1

C_i	dm_i	dm_c	f_i
ppm	kg/h	kg/h	t/h
0		0	0
	0.01		
2.1		0.01	3.33
	0.02		
3		0.03	7.81
	0.04		
6		0.07	11.38
	0.01		
6.4		0.08	12.51
	0.2		
10.8		0.28	25.66
	0.14		
15.6		0.42	26.53
	0.06		
20		0.48	24.23
	3.2		
207		3.69	17.82
	1.69		
322.7		5.38	16.67

The input data for problem 3.2 is given in Table C.4.

Table C.4. Sample Input Data of ProgramA.MB for Problem 3.2

Operation	$f_{i,in}$	$C_{i,in}^{\lim}$	$C_{i,out}^{\lim}$
i	t/h	ppm	ppm
1	36.36	25	80
2	44.31	25	90
3	22.86	25	200
4	60.00	50	100
5	40.00	50	800
6	12.50	400	800
7	5.000	400	800
8	10.00	0	100
9	80.00	50	300
10	43.33	150	300

The output data of Mass problem calculation for problem 3.2 is given in Table C.5.

Table C.5. Sample Output Results of Program A.MB for Problem 3.2

C_i	dm_i	dm_C	f_i
ppm	kg/h	kg/h	t/h
0		0	0
	0.25		
25		0.25	10
	2.86		
50		3.11	62.13
	8.83		
80		11.93	149.17
	2.58		
90		14.51	161.25
	2.13		
100		16.64	166.42
	7.15		
150		23.79	158.61
	9.32		
200		33.11	165.53
	16.33		
300		49.44	164.8
	4		
400		53.44	133.6
	23		
800		76.44	95.55

The input data for problem 3.3 is given in Table C.6.

Table C.6. Sample Input Data of ProgramA.MB for Problem 3.3

Operation	$f_{i,in}$	$C^{\lim}_{i,in}$	$C^{\lim}_{i,out}$
i	t/h	ppm	ppm
1	350	6.0	322.7
2	360	6.4	15.6
3	360	2.1	10.8
4	60	20.0	207.0
5	50	0.0	3.0

The output data of Mass problem calculation for problem 3.3 is given in Table C.7.

Table C.7. Sample Output Results of Program A.MB for Problem 3.3

C_i	dm_i	dm_c	f_i
ppm	kg/h	kg/h	t/h
0		0	0
	0.11		
2.1		0.11	50
	0.37		
3		0.47	157.93
	1.08		
6		1.55	258.85
	0.28		
6.4		1.84	287.03
	4.71		
10.8		6.54	605.85
	3.41		
15.6		9.95	637.83
	1.54		
20		11.49	574.51
	76.67		
207		88.16	425.91
	40.5		
322.7		128.66	398.7

Programme to draw the limiting composite curve for problem 3.1:

```
x=[0,0,0.02,0.06,0.08,0.27,0.41,0.48,3.68,5.37];
y1=[0,2.1,3.0,6.0,6.4,10.8,15.6,20,207,322.7];
y2=38.049*x;
plot(x,y1,'black')
hold on
plot(x,y2,'--black')
hold off
ylabel('Concentration [ppm]')
xlabel('Mass load [kg/h]')
title('Limiting concentration composite curve')
```

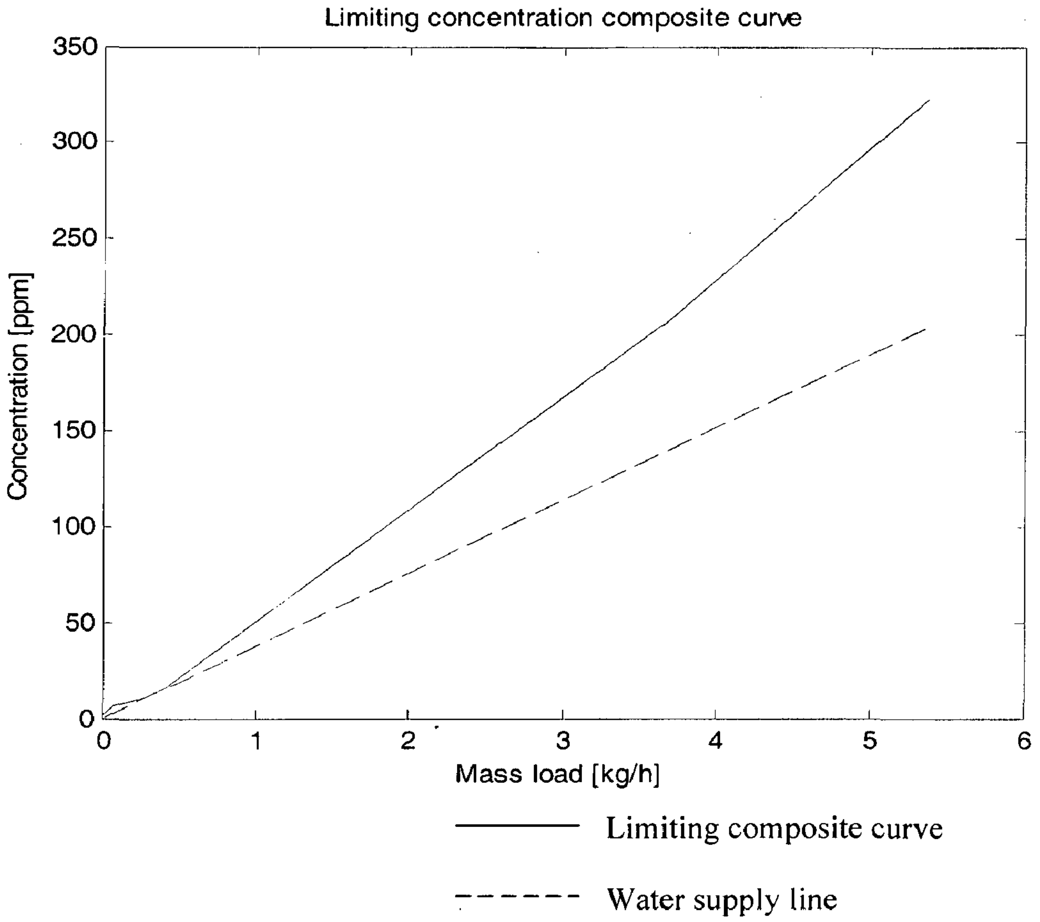


Fig.C.1. Limiting concentration curve for Problem 3.1

Result: The minimum fresh water consumption is 26.53 t/h.

Programme to draw the limiting composite curve for problem 3.2:

```
x=[0,0.25,3.09,11.89,14.47,16.59,23.74,33.05,49.38,53.38,
65.88,76.38];
y1=[0,25,50,80,90,100,150,200,300,400,600,800];
y2=6.0994*x-1.189;
plot(x,y1,'black')
hold on
plot(x,y2,'--black')
hold off
ylabel('Concentration [ppm]')
xlabel('Mass load [kg/h]')
title ('Limiting concentration composite curve')
```

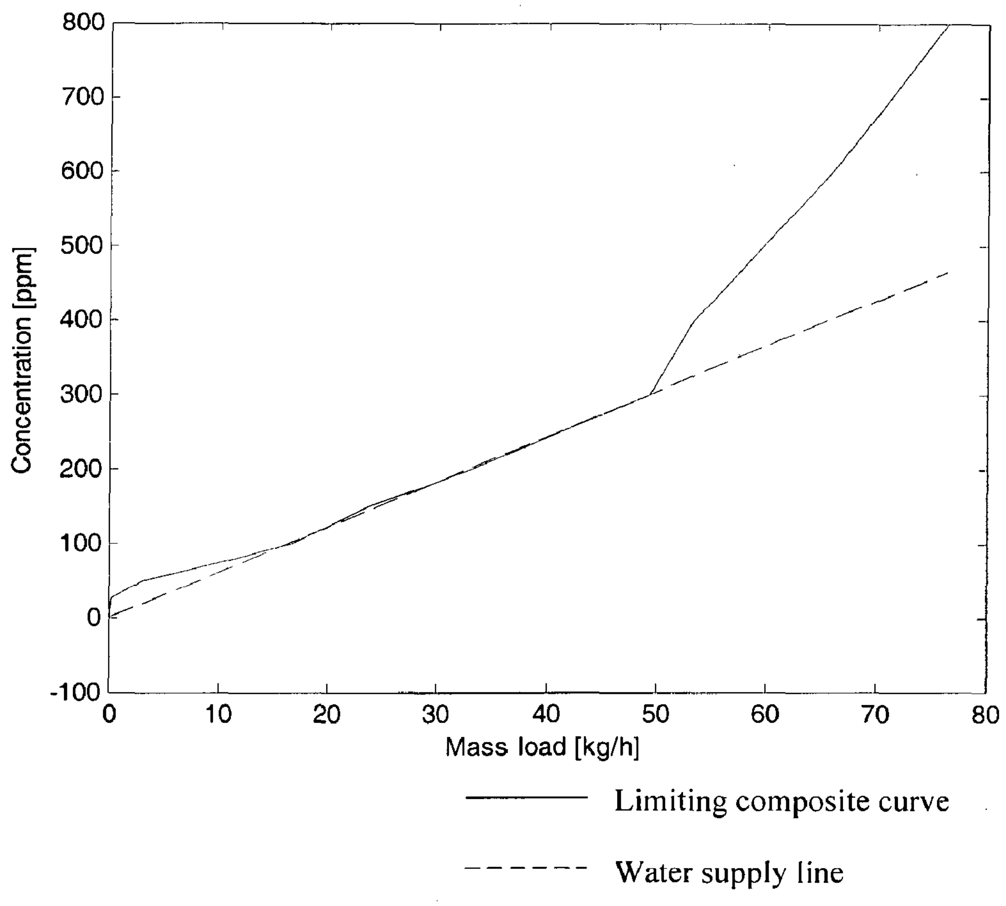


Fig.C.2. Limiting concentration curve for Problem 3.2

Result: The minimum fresh water consumption is 166.42 t/h

Programme to draw the limiting composite curve for problem 3.3

```
x=[0,0.11,0.47,1.55,1.84,6.54,9.95,11.49,88.16,128.66];
y1=[0,2.1,3.0,6.0,6.4,10.8,15.6,20,207,322.7];
y2=1.667*x;
plot(x,y1,'black')
hold on
plot(x,y2,'--black')
hold off
ylabel('Concentration [ppm]')
xlabel('Mass load [kg/h]')
title('Limiting concentration composite curve')
```

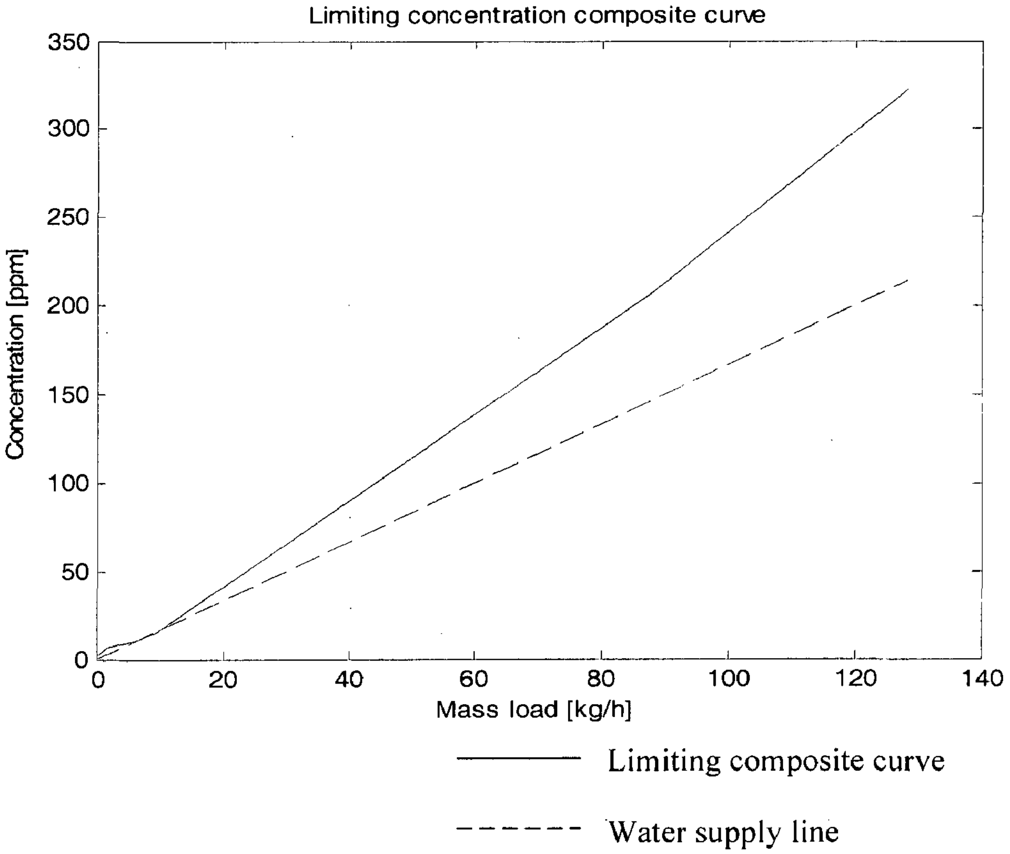


Fig.C.3. Limiting concentration curve for Problem 3.3

Result: The minimum fresh water consumption is 637.83 t/h

Program B.MB :

Programme to find the cost analysis against modifications

```
function costanalysis()
format long;
clf;clc;
options=input('input the number of data points you wish
to enter::  ')
for(i=1:options)
    disp('Enter the data for option ' );
    capitalinv(i)=input('Enter the Capital investment::
');
    watersaving(i)=input('Enter the water saving::  ');
    annualbenefit(i)=input('Enter the annual benefit::
');
 paybacktime(i)=(capitalinv(i)/annualbenefit(i))*12;
end
disp('The paybacktime is :: ');
disp(paybacktime);
totalannualbenefit=0;
totalcapital=0;
totalwater=0;
for(i=1:options)

totalannualbenefit=totalannualbenefit+annualbenefit(i);
    totalcapital=totalcapital+capitalinv(i);
    totalwater=totalwater+watersaving(i);
end
totalbenefit=num2str(totalannualbenefit)
totalannualwater=num2str(totalwater)
totalcapitalinvestment=num2str(totalcapital)
```

OUTPUT OF THE COST ANALYSIS BY THE PROGRAME BY COST ANALYSIS

Example 1

```
input the number of data points you wish to enter:: 6
options =     6
Enter the data for option
Enter the Capital investment:: 6760
Enter the water saving:: 1.75
Enter the annual benefit:: 11810
Enter the data for option
Enter the Capital investment:: 1040
Enter the water saving:: 8.1
Enter the annual benefit:: 54640
Enter the data for option
Enter the Capital investment:: 0
Enter the water saving:: 12.57
Enter the annual benefit:: 84790
Enter the data for option
Enter the Capital investment:: 44980
Enter the water saving:: 8.12
Enter the annual benefit:: 54780
Enter the data for option
Enter the Capital investment:: 0
Enter the water saving:: 2.71
Enter the annual benefit:: 18280
Enter the data for option
Enter the Capital investment:: 1240
Enter the water saving:: 0.83
Enter the annual benefit:: 5600
The paybacktime is ::
  6.86875529212532  0.22840409956076              0  9.85323110624315              0
2.65714285714286
totalbenefit = 229900

totalannualwater = 34.08

total capital investment =54020
```

Problem 3.2:

```
input the number of data points you wish to enter:: 5

options =     5

Enter the data for option
Enter the Capital investment:: 6760
Enter the water saving:: 6.22
Enter the annual benefit:: 41957
Enter the data for option
Enter the Capital investment:: 1040
Enter the water saving:: 14
Enter the annual benefit:: 94436
Enter the data for option
Enter the Capital investment:: 1240
Enter the water saving:: 66.56
Enter the annual benefit:: 448573
Enter the data for option
Enter the Capital investment:: 0
Enter the water saving:: 40
Enter the annual benefit:: 269818
Enter the data for option
Enter the Capital investment:: 44980
Enter the water saving:: 30
Enter the annual benefit:: 202363
The paybacktime is ::
  1.93340801296566   0.13215299250286   0.03317185831515                0
2.66728601572422


totalbenefit = 1057147


totalannualwater = 156.78


totalcapitalinvestment = 54020
```

Problem 3.3:

```
input the number of data points you wish to enter:: 6
options =     6
Enter the data for option
Enter the Capital investment:: 6550
Enter the water saving:: 42
Enter the annual benefit:: 11340
Enter the data for option
Enter the Capital investment:: 1000
Enter the water saving:: 340
Enter the annual benefit:: 91800
Enter the data for option
Enter the Capital investment:: 0
Enter the water saving:: 360
Enter the annual benefit:: 97260
Enter the data for option
Enter the Capital investment:: 43640
Enter the water saving:: 195
Enter the annual benefit:: 52650
Enter the data for option
Enter the Capital investment:: 0
Enter the water saving:: 65
Enter the annual benefit:: 17550
Enter the data for option
Enter the Capital investment:: 1200
Enter the water saving:: 20
Enter the annual benefit:: 2700
The paybacktime is ::
  6.93121693121693  0.13071895424837             0  9.94643874643875
0  5.33333333333333


totalbenefit = 273300


totalannualwater = 1022


totalcapitalinvestment = 52390
```