An Overview on Different Water Pinch Methods
for Industrial Water and Wastewater Minimization

Naser Mehrdadi, Gholamreza Nabi Bidhendi, Shahin Mohammadnejad*

Department of Environmental Enqineering, Faculty of Environment, University of Tehran, Iran

Abstract

In this paper, six methods of water pinch analysis are introduced to illustrate the advantages and disadvantages of each method. Although, these methods can be used in some industries which generate single contaminant during their processes, otherwise all contaminants can be considered as a single contaminant, but actually it is impossible. On the case of multiple contaminants, we can apply pinch analysis by using mathematical programming methods. While graphical methods are unusable in the most situations, some researchers such as Wang and Smith, Gomez and James G. Mann, have developed their methods to cover the multiple contaminant problems. However, more applicable results may be achieved by using mathematical methods as discussed in relation to the Tan and Yee methods. Among the methods considered, Gomes' mass transferring network is the most satisfactory for use in most industries. This method can be used for both single and multiple contaminant problems.

Keywords: minimization, mass exchange, reuse, regeneration, water pinch, pinch analysis.

مروری بر روش‌های مختلف پینچ آبی برای کاهش مصرف آب و تولید پساب در صنعت

ناصر مهردادی ، غلامرضا نبی بیدهندی، شاهین محمدنژاد*

گروه مهندسی محیط زیست، دانشکده محیط زیست، دانشگاه تهران

چکیده

آنالیز پینچ آب یک تکنیک سیستماتیک برای طراحی بهینه و بروزرسانی شبکه‌های بازیافت آب، انرژی و جرم می‌باشد. محققان زیادی بر روی این تکنولوژی کار کرده‌اند. روش‌های مختلفی که این محققان در کارهای خود استفاده نموده‌اند شامل روش‌های گرافیکی، عددی و برنامه‌نویسی ریاضی است. هر کدام از این روش‌ها مزایا و معایب خاص خود را دارند. به عنوان مثال مبنای اکثر روش‌های گرافیکی و عددی، انتقال جرم آلاینده می‌باشد. در حالی که در بسیاری از عملیات‌های مصرف کننده آب، انتقال جرم صورت نمی‌گیرد . از معایب دیگر این روش‌ها آن است که اکثر این روش‌ها بر مبنای انتقال فقط یک نوع آلاینده می‌باشد. در صورتی که کمتر صنعتی یافت می‌شود که فاضلاب واحدهای مختلف آن فقط حاوی یک نوع آلاینده باشد. هدف از این مقاله، انجام مقایسه‌ای بین روش‌های مختلف آنالیز پینچ آب، بررسی مزایا و معایب هر کدام از این روش‌ها و انتخاب بهترین روش می‌باشد.

کلیدواژه‌ها: کمینه سازی ، شبکه‌های تبادل جرم، استفاده مجدد از آب، احیاء مجدد ، پینچ آب ، آنالیز پینچ آب.

* Corresponding author. *E-mail Address:* mohammadnejads@gmail.com

Introduction

Water Pinch Analysis is a systematic technique for optimum designing and updating water, energy and mass recycling networks.

Many researchers have studied this technology and applied several methods such as graphical and numerical methods and mathematical programming. Each method may have some special advantages and disadvantages. For example almost all of graphical and numerical methods have been developed on the basis of mass contaminant transfer, but this does not happen within most water-use operations. Also, most of these methods are used for a single contaminant, while there are few industries which generate only a single contaminant during their processes.

The pattern of water consumption in industrial and non-industrial complexes with high rates of water consumption is a very important issue. Furthermore qualitative and quantitative criteria must be indicated. So it needs a technical insight for water management, conservation and reuse. With introducing of zero discharge idea, application of pinch technology for water management is very important and it is necessary to consider several aspects of water consumption, balance and recycling. Pinch technology refers to mass exchange integration within water-use operations, so that the main network application is not disordered because this technology is used in the same network.

Pinch analysis is an integrated tool that has been developed initially for energy efficiency since the last of 1990s. El-Halwagi and Harnad (1992) described the role of the wastewater network for mass integration. Then Wang and Smith (1994) used the water pinch method for water-use systems based on mass transfer. Dhole *et al.* (1996) applied a more different method than Wang and Smith. Castro *et al.* (1999) have illustrated how to calculate the minimum freshwater utility.

Gomes (2001) established an algorithm method based on concentration. El-Halwagi (2006) again described the role of wastewater network for mass integration. Manan *et al.* (2006) implemented a water cascade analysis at a mosque in Malaysia and Gomes *et al.* (2006) used the water source diagram by mapping inlet and outlet source streams.

Water pinch technology has been currently developed and applied for several cases. Some possibilities such as wastewater regeneration, reuse and the wastewater regeneration recycle are other abilities of water pinch technology. In addition, this technology is used for multiple contaminant conditions.

Materials and Methods

There are four general possibilities for water pinch analysis:

a. **Process Changes:** Water requirements can be minimized by changing the technology used in operations. It will be possible when the current equipment is changed, removed or refined.

b. **Water Reuse**: The outlet stream from some processes can be used as an inlet stream by others. Equally, wastewater from a process can be used by the other directly, if the contaminant concentration from previous process does not disorder the next process. It reduces the amount of freshwater required and wastewater generated, while it will not affect the outlet contaminant load; the outlet stream from a process does not re-enter the same process.
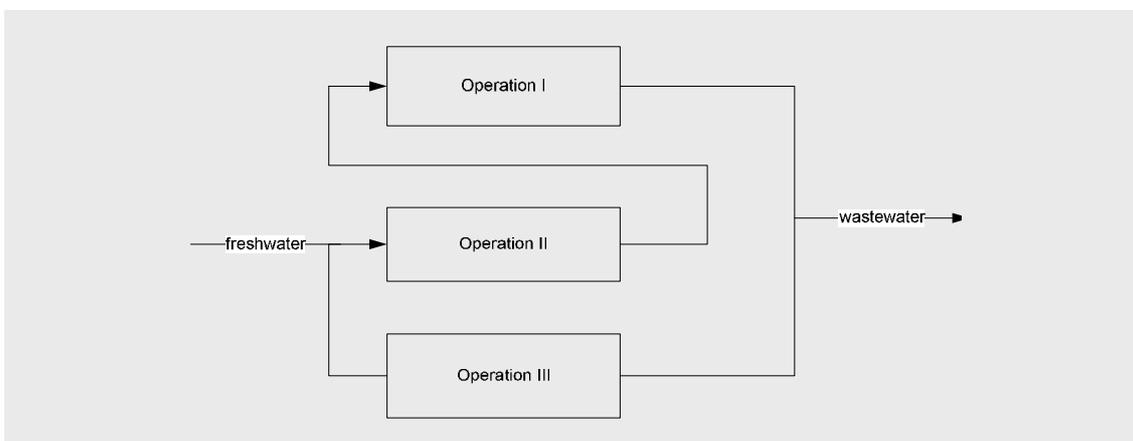
Figure 1. Water minimization because of reusing it during processes.

c. **Regeneration-Reuse**: Partial treatment can remove contaminants from wastewater which otherwise would prevent its reuse and then it can be reused in other processes. Regeneration may be done by filtration or activated carbon adsorption. Accordingly, the contaminant load of water and wastewater is reduced.
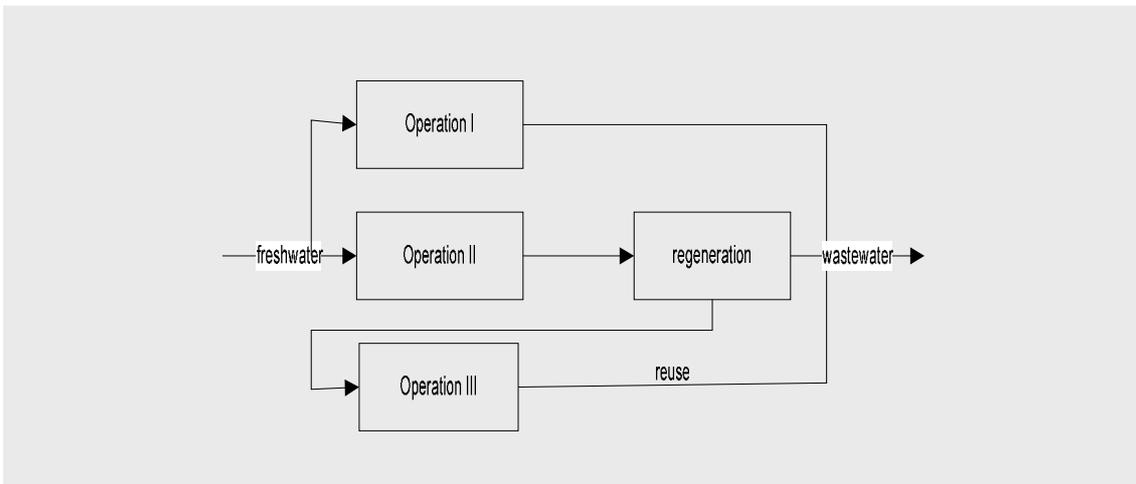
Figure 2. Water minimization because of wastewater regeneration reuse.A

d. **Regeneration-Recycle**: Wastewater can be regenerated to remove those contaminants which have built up and then water is recycled. In this case water can re-enter the process in which it has previously been used.
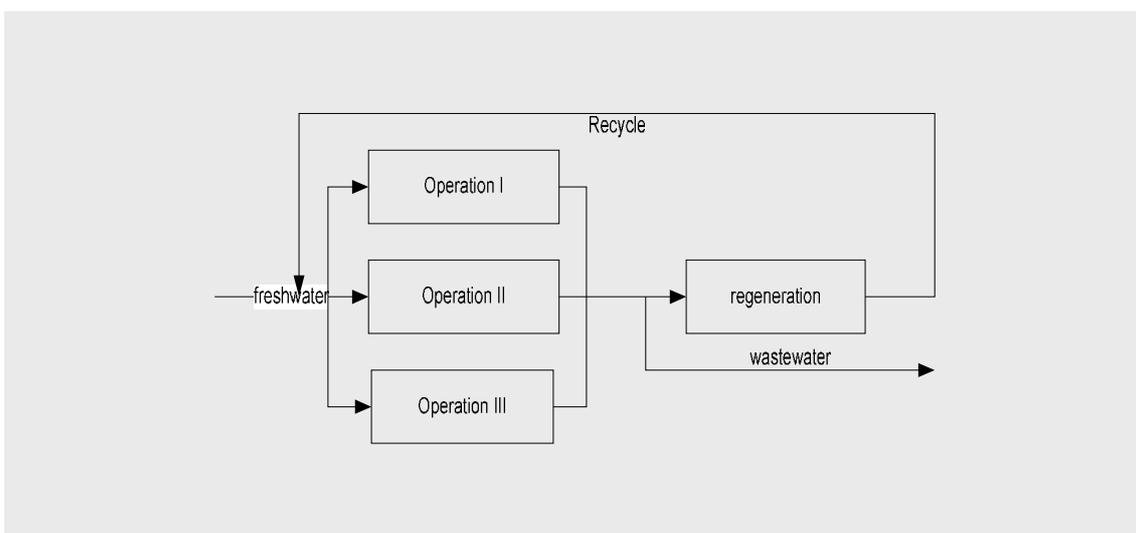
Figure 3. Water regeneration recycling.

Water-use operations in the processes are classified as below:

- **Mass-Transfer-Based Operations**: In these operations some special contaminants from a rich stream are transferred to a lean stream with a low concentration.

- **Non Mass-Transfer-Based Operations**: Water is not considered as a washing agent, so the water flow-rate will be different.

According to aforementioned classification for water-use, generally in this paper the following methods have been reviewed:

- The Wang and Smith Model
- The Dhole *et al.* Model
- The Sorin and Bedard Model
- The Hallale Model
- The Yin Ling Tan Model
- The Gomes Model

Results and Discussion

Wang and Smith Model (1994)

Wang and Smith introduced a graphical methodology for water and wastewater minimization. This method was established on the basis of developing a pinch technique for heat integration. Each water-use operation is supposed as a mass exchange process. The curve related to each operation is drawn by specifying a maximum acceptable inlet and outlet concentration of that operation. This curve touches the water supply line (which starts from zero point) at one or more points. These points are pinch points.

It must be pointed out that this method is based on a contaminant concentration curve versus mass load. Figure 4 shows these curves (Wang and Smith, 1994).

Dhole *et al.* Model (1996)

Dhole *et al.* (1996) demonstrated that tha Wang and Smith model may encounter some deficiencies. Some operations such as washing, extraction and etc. are modeled easily by this method. However, many operations such as reactors, boilers, cooling towers and so on are not classified as mass exchange operations. Water flow-rate is the main factor in these operations. Furthermore the modeling of some operations which several water streams with different concentrations enter or leave them is difficult (Figure 5).

Dhole *et al.* (1996) overcame this problem by proposing a method in which each operation is considered according to how it has inlet and outlet stream while flow-rates and concentrations are different.

To make the demand composite curve, all inlet streams are drawn simultaneously. The horizontal axis shows the water flow-rate while the vertical axis indicates the contaminant mass load. The outlet streams from operations are drawn to make the source composite curve the same as inlet streams.
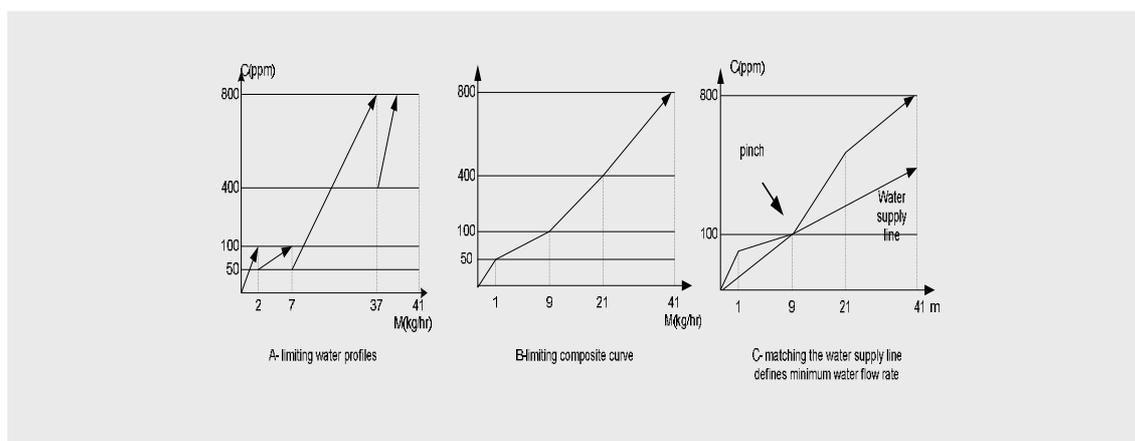
Figure 4. Limiting water profile, water supply line and concentration composite curve.
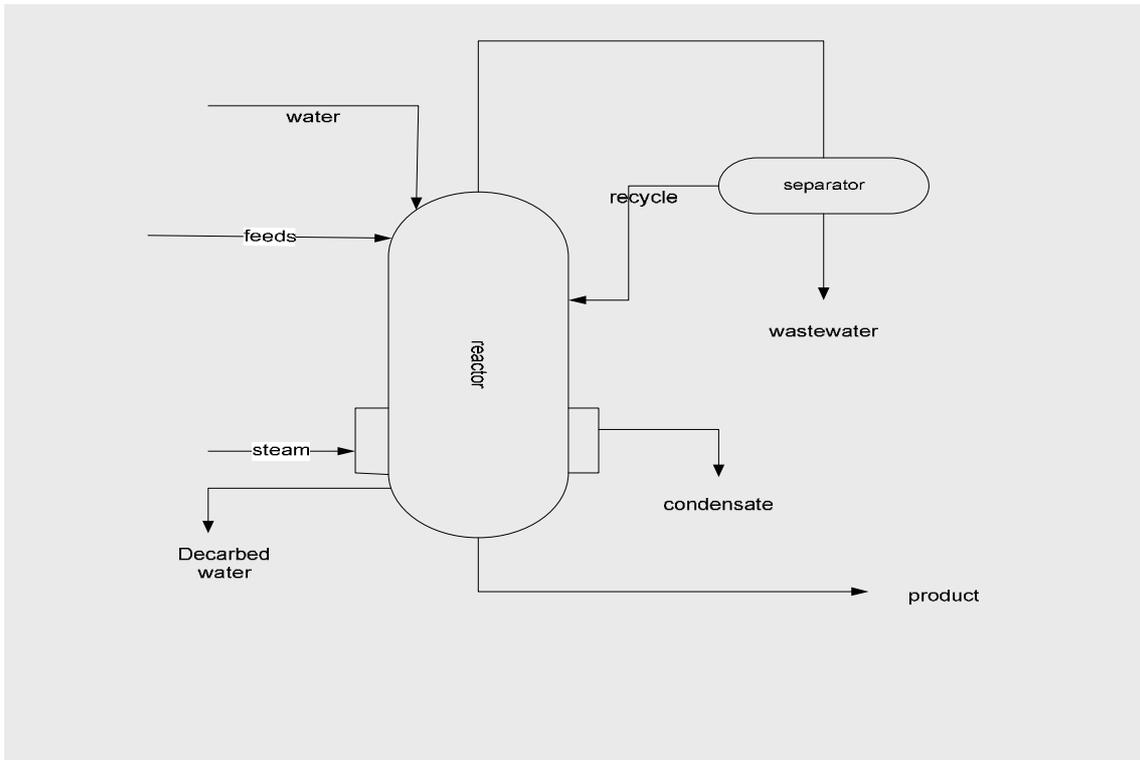
Figure 5. A typical reactor that may not be classified as a mass exchange process.
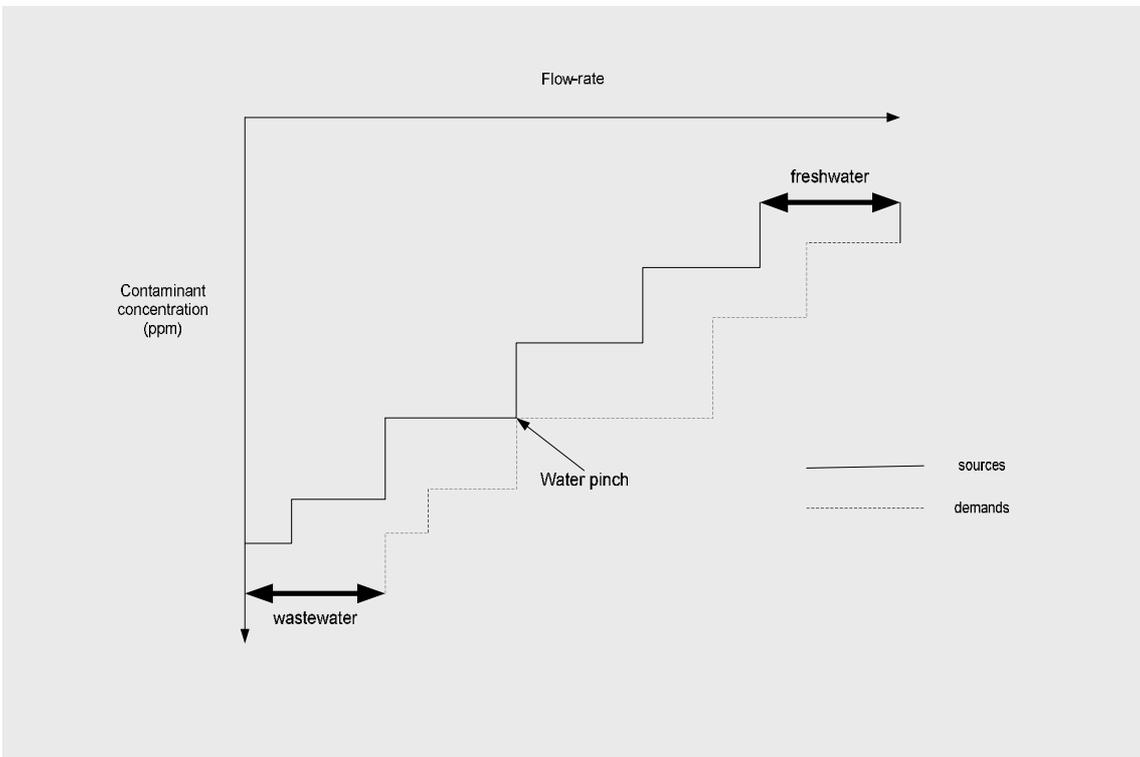
Figure 6. A typical concentration composite curve (Dhole *et al.* (1996))

These two curves are drawn in a coordinated system and touch each other at one point. This point shows the potential for water reuse. Dhole *et al.* (1996) pointed that pinch point divides problem into two parts: above and below the pinch point.

To achieve freshwater minimization, the freshwater above the pinch point is not used and sources above the pinch are discharged as wastewater. But this is not too exact because mixing water sources can change the shape of the source composite curve. For example, Figure 7 shows how two sources have

been mixed and made a new source with composite concentration.

Sorin and Bedard Model (1999)

Sorin and Bedard proposed a method based on applying an "Evolutionary Table". In this method operation data are indicated first (Table1). An Evolutionary Table is then drawn up based on these data and after completing it the results are saved in a design table (Table2).
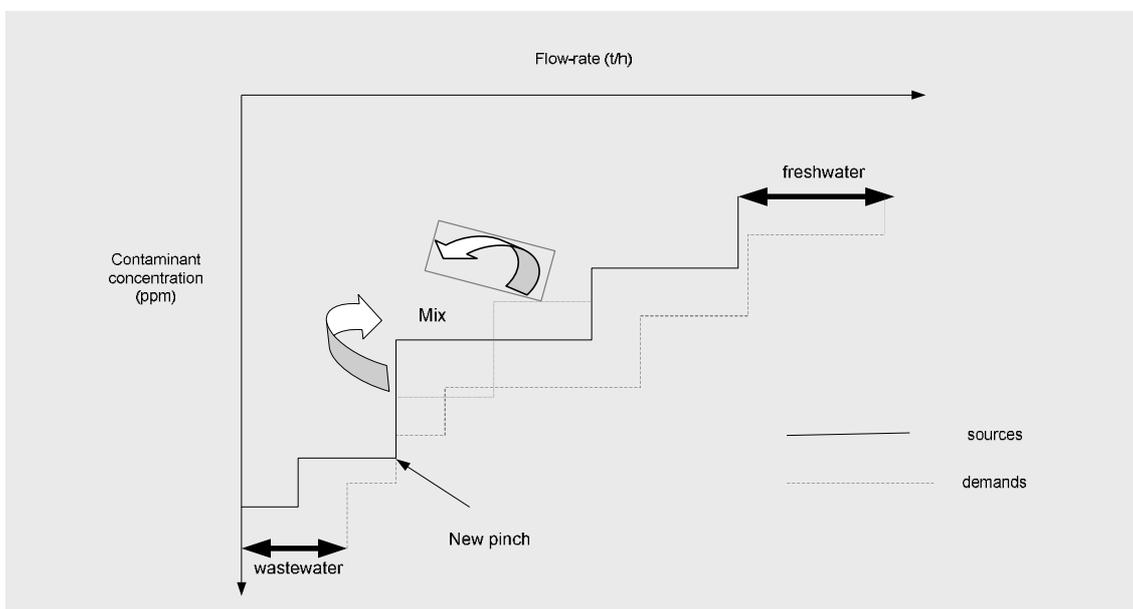
Figure 7. A typical mixing of water sources and changing pinch point

Table1- A typical limiting water data.

Process	Water$_{in}$ t/h	Water$_{out}$ t/h	C $_{in}$ ppm	C $_{out}$ ppm	Mass load of contaminant kg/h
1	120	120	0	100	12
2	80	80	50	140	7.2
3	80	–	50	–	–
4	140	140	140	180	5.6
6	80	80	170	230	4.8
7	195	195	240	250	1.95

Table 2- A typical design table.

Water demand	Concentration, ppm	Water Source						
		Process 6out	Process 5 out	Process 4 out	Process 2 out	Process 1 out	Fresh water	
Process1in	0	0	0	0	0	0	120	
Process2in	50	0	0	0	0	40	40	
Process3in	50	0	0	0	0	40	40	Above Global pinch
Process4in	140	0	0	30	80	30	0	
Process5in	170	0	0	70	0	10	0	
-----------	180	---	---	-----	----	----	----	Global pinch
Process6in	240	110	80	5	0	0	0	Below Global pinch
Wastewater	_	85	0	35	0	0	0	

This idea originates from a numerical method to indicate minimum freshwater and wastewater without using graphical solutions. If there is more than one pinch point this idea would not indicate them correctly and could present wrong guidelines for process regeneration and optimization. So, the pinch point is not the best result for process optimization in this method.

Hallale *et al.*, Model (2001)

This method uses a Water Surplus Diagram (WSD). At first a new form of water demand and source composite curve based on the data is drawn. There are three differences between this model and the one of Dhole *et al.*:

1- The vertical axis shows water purity not contaminant concentration.

2- The initial water flow-rate is supposed in curve.

3- Both curves start at zero point and the curves do not move to find the pinch point. Accordingly, the source composite curve does not place above all demand composite curve.
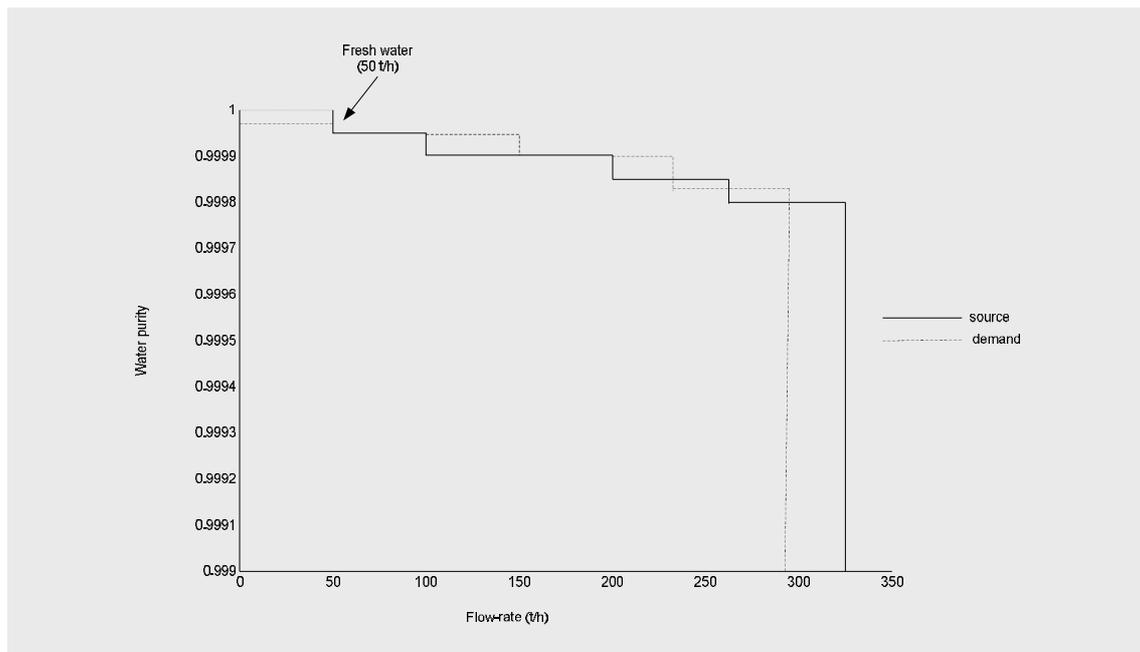
Figure 8. A typical new demand-source composite curve.

The next step is running the feasibility test for supposed freshwater flow-rate. In this stage water surplus diagram is drawn.

As with Figure 9, a part of the diagram is placed in a negative area with considering supposed fresh water flow-rate. This means fresh water must be added.

This method is used where some operations may not be classified as processes of contaminant mass exchange. Water losses or collecting and modeling operations with several inlets and outlets may be considered with this method. But its weakness in estimating minimum water utility and also applying the long trial and error method are some of the disadvantages of this method.
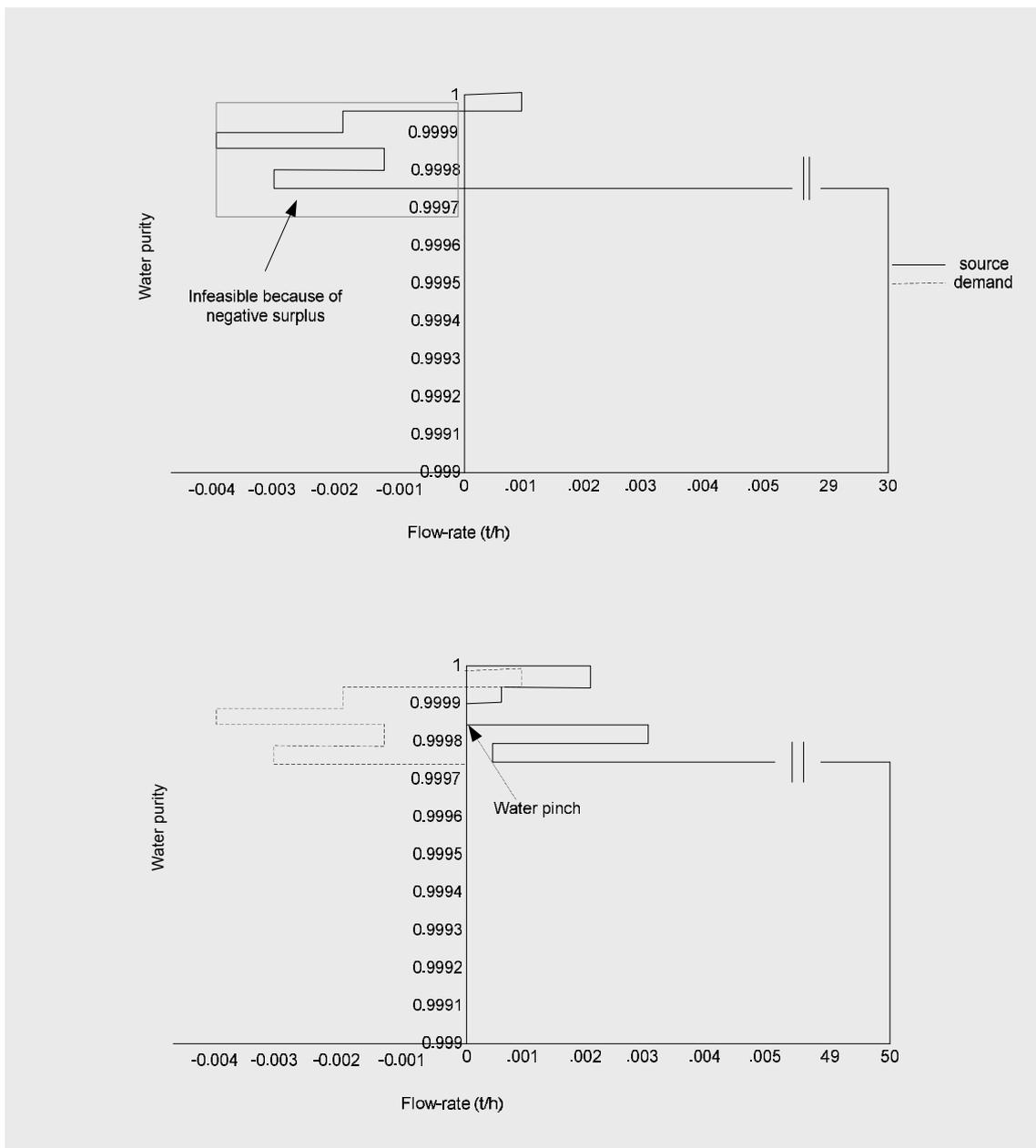
Figure 9. A typical water surplus diagram.

Yin Lin Tan Model (2002)

The Yin Lin Tan Model is based on the Water Cascade Table (WCT) and is used for both continuous and batch processes. The WCT originates from the Water Surplus Diagram. Accordingly, there is no limitation for contaminant transfer. On the other hand, it does not use trial and error solution to estimate minimum utility target (Table3).

A time-dependent WCT is used in the batch processes. This method can determine minimum required freshwater and easily locate the pinch point. However, this method does have some difficulties:

1- There is no method for estimating initial freshwater flow-rate in some cases in which the total water flow-rate is equal to the wastewater flow-rate.

2- There is no method for estimating the initial freshwater flow-rate for some cases in which the total water flow-rate is equal to or more than the wastewater flow-rate and also when there is more than one water demand and source.

3- When there is no negative value in the cumulative water surplus column, it does not tend to achieve the answer.

Figure 10 shows the WCT process by Tan *et al.* (2002). Yee *et al.* (2003) modified this process as indicated in Figure 11.

Table 3-A typical Water Cascade Table.

Conc.C (ppm)	Purity,p	$\sum F_{D,j}$	$\sum F_{S,i}$	$\sum F_{D,j} + \sum F_{S,i}$	Cum.Water flow-rate,kg/s	Water surplus,kg/s	Cum.Water surplus,kg/s
0	1.000000	-1.2	0.8	-0.4	2.06		
10	0.999990	-5.8		-5.8	1.66	0.0000166	0.0000166
14	0.999986		5.0	5	-4.14	-0.0000166	0
25	0.999975		5.9	5.9	0.86	0.0000095	0.0000095
34	0.999966		1.4	1.4	6.76	0.0000608	0.0000703
					8.16	8.1600000	8.1600703

Data

F_{WD} and F_{WS} —NO→ F_{WD} only —YES→ $F_{DW} = \sum F_{WDi}$ $(F_{WW} = 0$

—NO→ F_{WS} ONLY $F_{WW} = \sum F_{WSj}$ $(F_{WS} = 0)$

$\sum F_{WDi} \geq \sum F_{WSj}$ —NO→ $P_{WS} \geq P_{WD}$ —YES→ $F_{WW} = \sum F_{WSj} + \sum F_{WDi}$

NO FRESHWATER IS NEEDED

—YES→

ESTIMATE FRESHWATER FLOW-RATE

$F_{FW.est} = \left| \sum F_{WDi} + \sum F_{WSj} \right|$

NEGATIVE VALUE IN COLUMN CUMULATIVE

$\left(\sum F \times \Delta P \right)$

—YES→ ESTIMATE A LARGER F_{FW}

—NO→

$F_{FW.est} = F_{FW}$

MINIMUM UTILITY
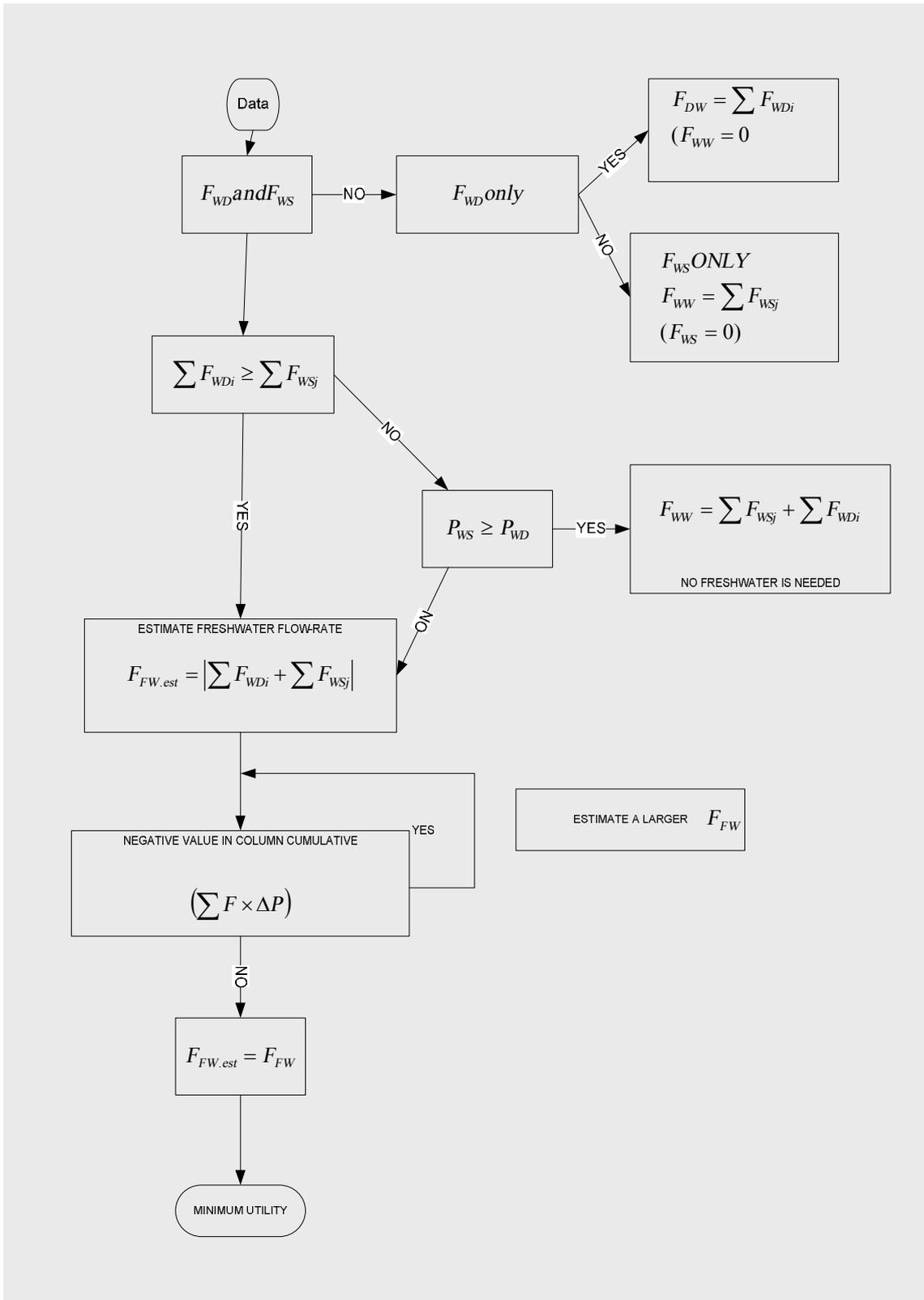
Figure 10. Tan Y. T. targeting process
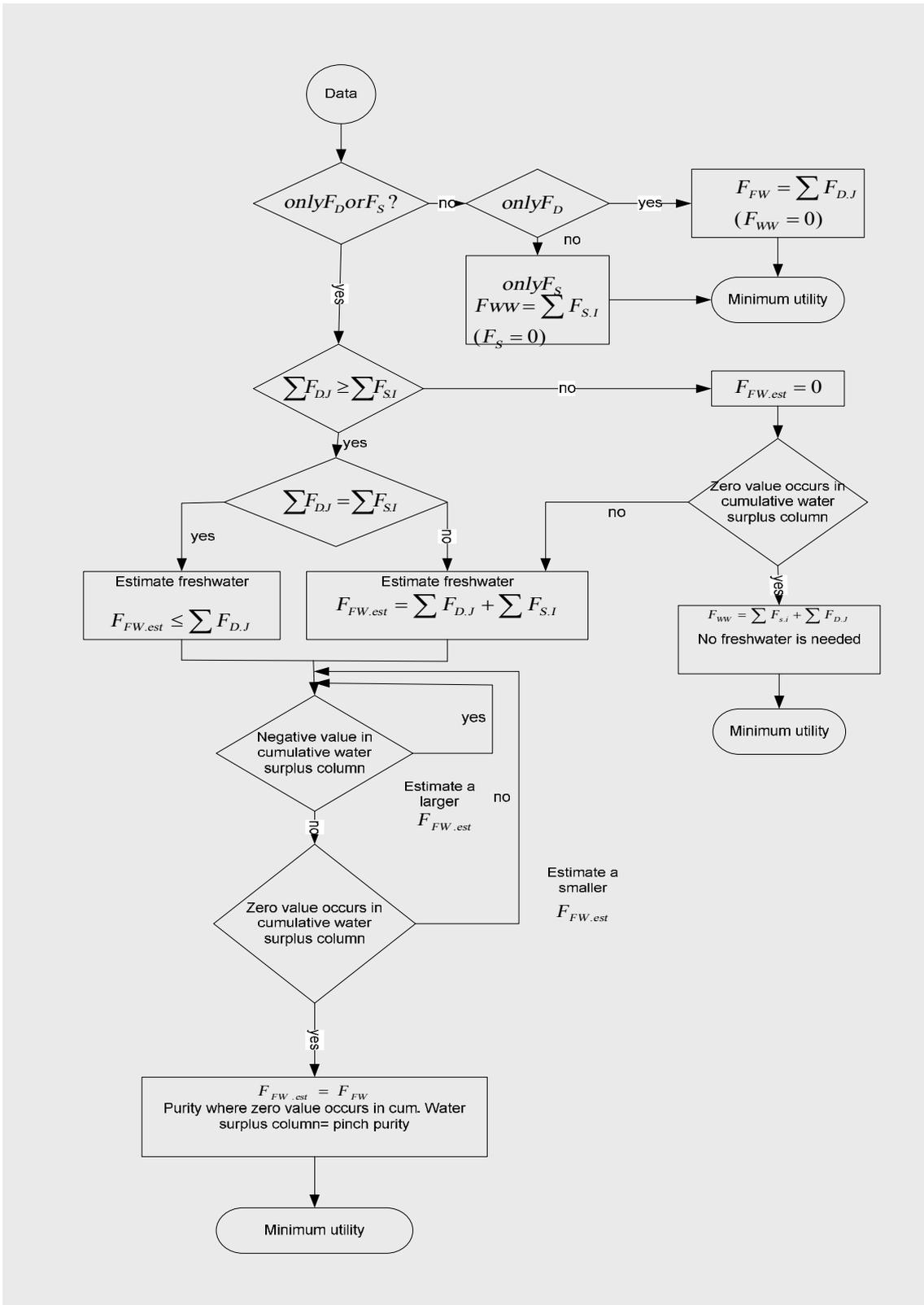
Figure 11. Yee F. C. process targeting.

Gomes Model (2006)

The Gomes Model is based on the Water Source Diagram (WSD) and, in fact, this method is the Castro modified Model (1999).There are several possibilities in this method such as reuse, multi water sources, water losses, regeneration and reuse, flow-rate constraints, regeneration and recycling. In this model, inlet and outlet concentrations of all operations have been shown as concentration intervals (vertical lines). The operation will be drawn as horizontal lines to concentration intervals.

Each operation is considered in a separate interval. The possibility of reuse and recycling is considered for each interval. In this method, estimation of minimum water and drawing the stream cycle is easy.

In fact, Gomes has designed an algorithm process with simple calculations. This method can be used for multiple contaminant processes with some changes.

Other Methods

Mann and Liu (1999) mentioned two Graphical methods and a Tabular Method. The Concentration Composite Curve, Block Diagram, Mass Content Diagram and Grid Diagram are used in the graphical method. In these methods reuse, regeneration and recycling may be applied easily. Also it is possible to use this method for multiple contaminant systems.

Manan *et al.*(2006) have applied water pinch analysis in an urban system by considering Water Cascade Analysis (WCA).

Conclusion

The problems of water shortages, environmental damages from wastewater discharge, increasing expenditures for freshwater supply and wastewater treatment have led researchers to find several options for freshwater utility minimization especially in the industries with high rates of water consumption.
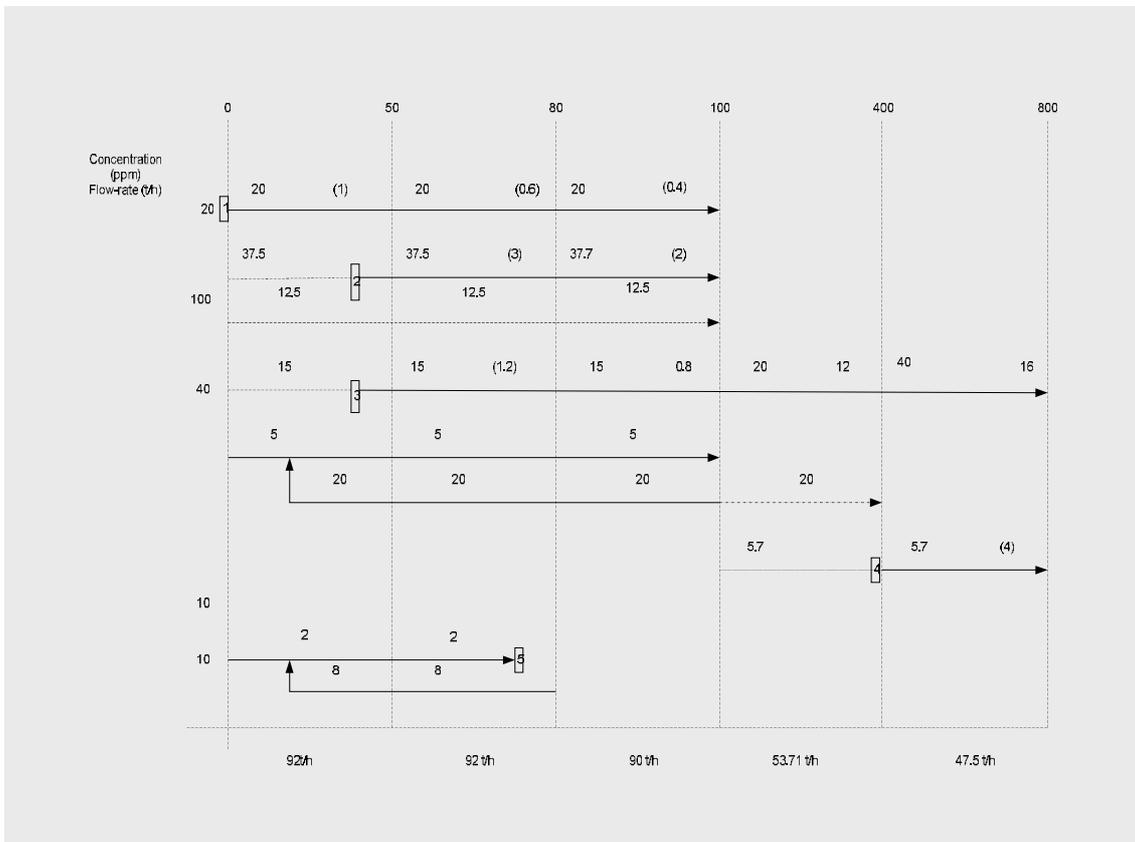
Figure 12. A typical Gomes mass exchange network.

Pinch analysis is an option for water and wastewater minimization. The methods mentioned in this paper are numerical and graphical methods for pinch analysis. These methods are easy for users, but they are not complete and correct in all cases and so there are some advantages and disadvantages for each method. Some methods overcome problems related to others. For example, the Dhole model has demonstrated and overcame some deficiencies related to the Wang and Smith model by modeling inlet and outlet streams with a different flow-rate and concentration. Among these methods, the Gomes mass transfer network is more satisfactory to use in most industries because there are several possibilities in this method such as multiple water sources, water losses, regeneration and reuse, flow-rate constraints as well as regeneration and recycling. Moreover, this method can be used for both single and multiple contaminant problems.

All of these methods can be used in some industries which generate a single contaminant during their processes; otherwise all contaminants should be considered as a single contaminant, but this is impossible.

On the case of multiple contaminants, we can apply pinch analysis by using mathematical programming methods while graphical methods are unable to address these in most situations. Some researchers, such as Wang and Smith and Gomez and Mann, have developed their methods to cover the multiple contaminant problems. However by using the mathematical programming methods more interesting results may be achieved.

Nomenclature

C   Contaminant concentration
P   Water purity value
D   Water demand
S   Water source
In   Inlet of operation
Out   Outlet of operation
WCT   Water cascade table

$\sum F_{WSj}$ Total flow-rate of source stream
F_{WW} Wastewater flow-rate
$\sum F_{WDi}$ Total flow-rate of demand stream
$F_{FW,est}$ Estimated freshwater flow-rate
F_{FW} Freshwater flow-rate

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