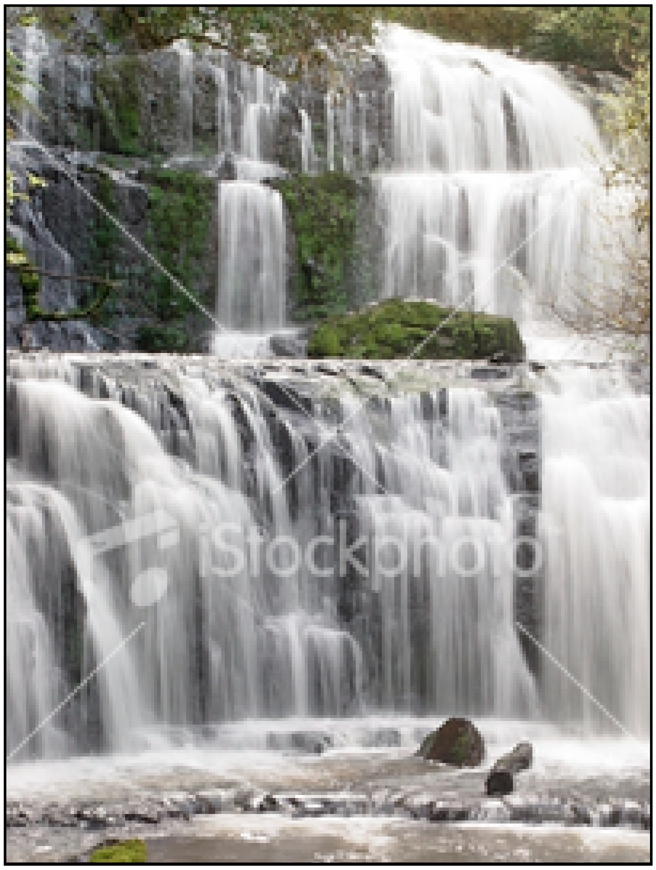
Use Cascade Analysis to Optimize Water Networks



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This numerical technique for identifying fresh water and wastewater targets eliminates the tedious and time-consuming steps of graphical targeting approaches. Use it to complement the graphical techniques in the design and retrofit of water-recovery networks.

The drive toward environmental sustainability and the rising costs of fresh water and effluent treatment have encouraged the process industries to find new ways to reduce fresh water and wastewater flowrates. At the same time, the development of systematic techniques for water reduction, reuse and recycling within a process plant has advanced. The introduction of water pinch analysis (WPA) as a tool for the design of optimal water networks has been one of the most significant advances in the area of water conservation over the last decade *(1–13)*.

Water pinch analysis is a systematic technique for implementing strategies to maximize water reuse and recycling through integration of water-using activities or processes. In the context of WPA, *reuse* means that the effluent from one unit is used in another unit and does not re-enter the unit where it has been previously used, whereas *recycle* allows the effluent to re-enter the unit where it has been used *(1)*. WPA involves two steps:

1. setting the minimum fresh water and wastewater flowrates (*i.e.*, the baseline water targets)
2. network design to achieve the baseline targets.

In setting the baseline targets and locating the pinch points, graphical techniques (such as composite curves) and numerical techniques (such as problem tables) have been used in heat

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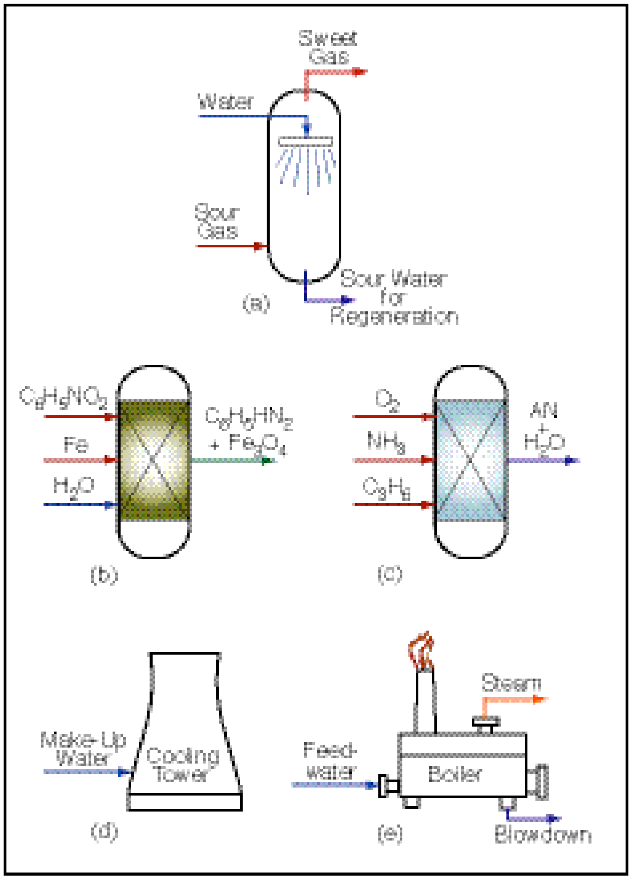
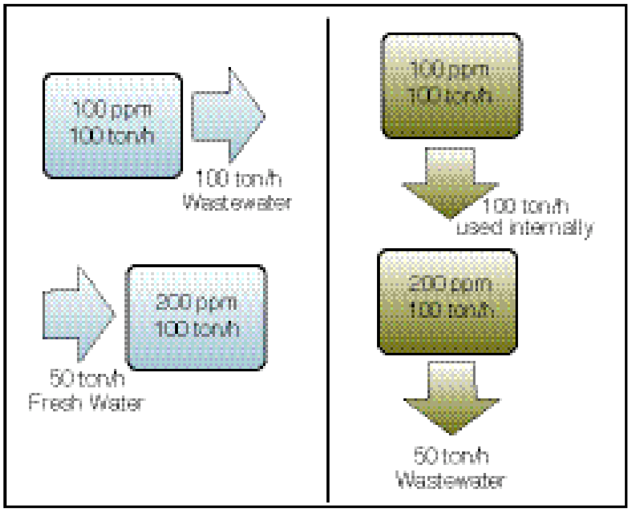


■ (Above) Figure 1. Many types of processes consume water (as sink) or produce it (as source): as a mass-separating agent (a), as a reactant (b), as a byproduct (c), as a cooling medium (d), or as feedwater for steam generation and wastewater from blowdown (e).



■ Figure 2. Water cascading reuses a spent water source to meet a lower-quality water sink.

(14) and mass *(15)* pinch analysis. These methods are usually used together because they play complementary roles. Although composite curves provide vital insights into the overall heat and mass transfer potentials in a process, they are tedious and time-consuming to draw, and their ability to yield quick and accurate minimum water targets is limited. On the other hand, numerical targeting tools offer accuracy and speed, and thus are more amenable to computer programming.

It is essential to have a good targeting tool to determine the baseline water targets numerically. Such a tool should:

- be capable of handling all types of water using-operations, including water used as a solvent or raw material, withdrawn as a product or byproduct in a chemical reaction, or utilized as heating or cooling media (Figure 1)
- consider both the flowrate and contaminant mass load for water reuse/recycle
- be non-iterative and able to quickly yield the exact baseline targets.

This article presents a numerical technique known as water cascade analysis (WCA) for establishing the minimum water and wastewater targets in a maximum-water-recovery (MWR) network *(12)*. The term *water cascade* refers to the reuse of a spent water source to satisfy a lower-quality water sink.

Figure 2 illustrates the concept of water cascading. In Figure 2a, a source produces 100 ton/h of wastewater with a concentration of 100 ppm, while 50 kg/s of water at 200

■ (Below) Figure 3. A preliminary water network for the paper mill example consumes nearly 2,000 ton/h of fresh water and generates almost 1,700 ton/h of wastewater.

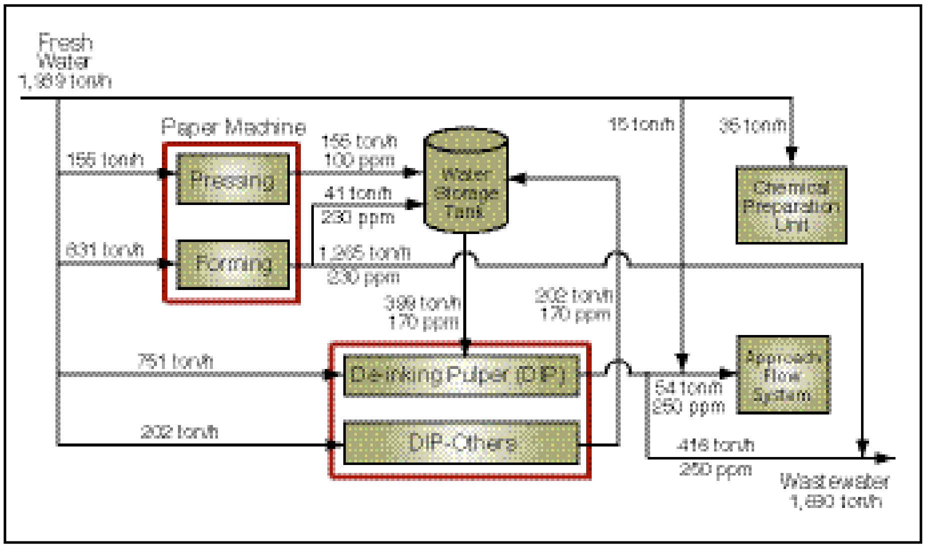


Table 1. Limiting water data for the paper mill example.

Water Sinks, D_j j	Stream	Flowrate (F_j), ton/h	Concentration (C_j), ppm
1	Pressing Section	155	20
2	Forming Section	831	80
3	DIP-Others	202	100
4	De-Inking Pulper (DIP)	1,150	200
5	Chemical Preparation (CP)	35	20
6	Approach Flow (AF)	69	200
Water Sources, S_j i	**Stream**	**Flowrate (F_i), ton/h**	**Concentration (C_i), ppm**
1	Pressing Section	155	100
2	Forming Section	1,306	230
3	DIP-Others	202	170
4	De-Inking Pulper (DIP)	470	250

Table 2. Interval water balance data for the paper mill example.

Level, k	Concentration (C_k), ppm	ΔC, ppm	$\Sigma_j F_j$, ton/h	$\Sigma_i F_i$, ton/h	$\Sigma_j F_j - \Sigma_i F_i$, ton/h	Net Water Source/ Sink
1	0				0	
		20				
2	20		190		–190	Sink
		60				
3	80		831		–831	Sink
		20				
4	100		202	155	–46	Sink
		70				
5	170			202	202	Source
		30				
6	200		1,219		–1,219	Sink
		30				
7	230			1,306	1,306	Source
		20				
8	250			470	470	Source
		999,750				
9	1,000,000				0	

ppm is needed to meet a water sink. Without water reuse, the entire 100 ton/h of wastewater must be treated and 50 ton/h of fresh water must be purchased. However, Figure 2b shows that reusing 100 ton/h of the cleaner 100-ppm water source to satisfy the 50-ton/h 200-ppm water sink avoids sending part of the water source directly to effluent. Doing so reduces both wastewater and fresh water flowrates by 50 ton/h.

A water-intensive paper mill process illustrates how WCA can be effectively used to set the baseline targets and optimize a water network that achieves zero discharge.

The paper mill example

A preliminary water network for a paper mill process (Figure 3) was not designed using WPA. The feedstocks, old newspapers and magazines, are blended with dilution water and chemicals to form pulp slurry called stock. The stock is sent to the forming section of the paper machine to form paper sheet. In the forming and pressing sections, fresh water (water sink) is fed to remove debris, while wastewater (water source) is removed from the stock during paper sheet formation. Some of the wastewater is sent to a water storage tank for reuse in other processes.

To remove printing ink from the main stock, the de-inking pulper (DIP) and its associated processes (denoted "DIP-Others") receive fresh water as well as spent water from the storage tank. The effluent from the DIP main process is mixed with fresh water to dilute the stock being pumped to the vacuum deaerator in the approach flow system (AF), which doses and uniformly mixes the components of the final suspension to be delivered to the paper machine. The effluent from DIP-Others is sent to the water storage tank. The chemical preparation (CP) unit (where the de-inking chemicals are prepared) also consumes fresh water to the dilute de-inking chemicals for use during ink removal in the DIP unit. Part of the wastewater from the forming section and the DIP unit are sent for effluent treatment before being discharged to the environment. The total fresh water consumption for this network is 1,989 ton/h and the total wastewater generation is 1,680 ton/h.

At first glance, this paper mill seems to have been designed with an extensive water recycling scheme. However, there may be room for improvement, and this is to be identified by WPA.

Table 1 summarizes the limiting data for this example — *i.e.,* the maximum permissible inlet (C_j) and outlet (C_i) concentrations for the water sinks and the water sources, respectively. The most significant water-quality factor, total suspended solids (TSS), is used for the analysis.

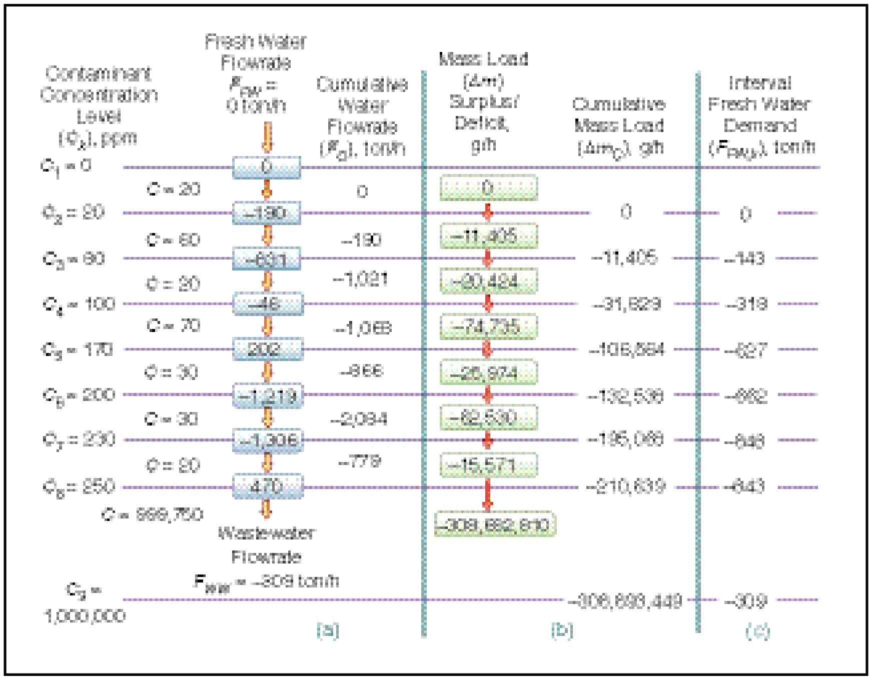
The water cascade analysis technique

The main objective of WCA is to establish the baseline water targets — *i.e.,* the minimum fresh water and wastewater flowrates for a process after using available water sources within the process to meet its water sinks. To achieve this, one has to fulfil both the flowrate and mass load requirements for all water-using processes under consideration.

The first step in WCA is to set up the interval water balance table (Table 2) to determine the net water source or net water sink at each concentration level. The first column of Table 2 contains the contaminant concentration levels (C) arranged in ascending order. Next, the water concentration difference (ΔC), the difference between concentrations at intervals k and k+1, is calculated:

$$\Delta C = C_{k+1} - C_k \qquad (1)$$

The next columns contain the total flowrates for the water



■ Figure 4. The water cascade diagram (a) is constructed with an assumed fresh water flowrate of 0 kg/s. The pure water cascade (b) is used to check the feasibility of the water cascade, and the interval fresh water demand, $F_{FW,k}$, (c) is used to determine the amount of fresh water needed in each purity range.

sinks ($\Sigma_j F_j$) and water sources ($\Sigma_i F_i$) at their corresponding concentration levels. Subtracting the total flowrate of the water sinks from the total water sources at each concentration level yields the net interval water flowrate ($\Sigma_i F_i - \Sigma_j F_j$), where a positive value indicates a net water source, and a negative value indicates a net water sink.

The next key step in WCA is to establish the fresh water and wastewater targets for the process. In doing so, it is important to consider both the water flowrate balance and the mass load requirement so that the true minimum water targets can be obtained.

The water flowrate balance involves the use of a water cascade diagram (Figure 4). In Figure 4a, a fresh water flowrate (F_{FW}) of 0 ton/h at a concentration of 0 ppm is assumed. The net water sink of 190 ton/h at the second concentration level (C_2 = 20 ppm) is cascaded to the third concentration level (C_3 = 80 ppm) to meet another water sink of 831 ton/h, giving a cumulative net sink (or the cumulative water flowrate, F_C) of 1,021 ton/h. The cascading process continues toward the lowest-quality (highest-concentration) level of 250 ppm. The cumulative water sink, or the wastewater flowrate (F_{WW}), at this point is 309 ton/h.

Next, the mass load allocation throughout the water network is determined via the mass load cascade (Figure 4b) in order to obtain true minimum water targets. First, the mass load (Δm) surplus or deficit at each concentration level of the water cascade is calculated. This is the product of the cumulative water flowrate (F_C) and the concentration difference (ΔC) across two concentration levels (Figure 4b). A mass load surplus (+) means that the load available from the water sources exceeds what is required, whereas a load deficit (–) means that there is still sufficient capacity to absorb the mass load in this concentration range. Cascading the mass load surpluses/deficits down the concentration intervals yields the cumulative mass load in Figure 4b.

Note that in Figure 4b, cumulative mass load deficits exist at all concentration levels. This indicates mass load infeasibility, which is the result of assuming zero fresh water flowrate (F_{FW} = 0 ton/h) during water cascading (Figure 4a). Thus, additional fresh water should be supplied to remove all flowrate and mass load deficits and yield a feasible water cascade.

Fresh water is to be supplied at the highest quality level (0 ppm). To minimize fresh water consumption, it is necessary to determine the minimum flowrate of fresh water, or the interval fresh water demand ($F_{FW,k}$), that will satisfy the total water requirement at each concentration level, C_k (Figure 4c). The interval fresh water demand will restore a feasible water cascade throughout the entire water network.

At each concentration level k, $F_{FW,k}$ is obtained by dividing the cumulative mass load (Δm_c) by the difference between the concentration level (C_k) of interest and that of the fresh water supply (C_{FW}) as follows:

$$F_{FW,k} = \Delta m_c / (C_k - C_{FW}) \qquad (2)$$

In Figure 4c, a negative value for $F_{FW,k}$ means that there is insufficient fresh water, whereas a positive $F_{FW,k}$ means that there is excess fresh water at the concentration level k.

To ensure that there is sufficient fresh water at all points in the network, a fresh water flowrate, F_{FW}, of exactly the same magnitude as the absolute value of the largest negative $F_{FW,k}$ should be supplied. This corresponds to the $F_{FW,3}$ value of –848 ton/h found at C_7 = 230 ppm in Figure 4c. Hence, a fresh water flowrate of F_{FW} = 848 ton/h is added at the highest-quality level (C_1 = 0 ppm) of the feasible water cascade in Figure 5. This in turn generates the minimum wastewater flowrate target of F_{WW} = 539 ton/h.

Note that a feasible water cascade is the one that results in

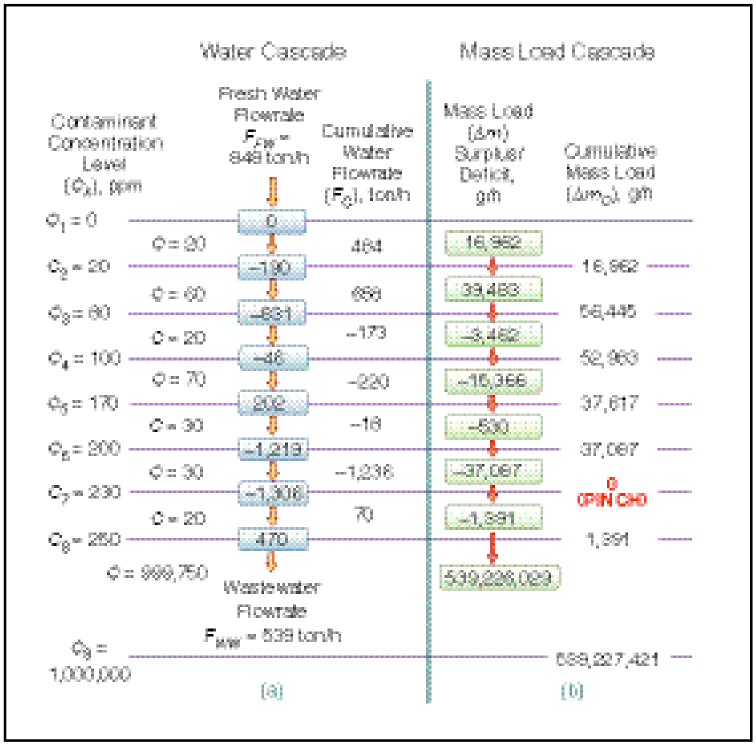


Figure 5. A feasible water cascade for the paper mill example consumes 848 ton/h of fresh water and generates 539 ton/h of wastewater.

a positive (or zero) value for the cumulative mass load cascade in Figure 5b. This means a 57% reduction in fresh water and 70% reduction in wastewater flowrates compared to the preliminary water network in Figure 3.

At the C_7 = 230 ppm in Figure 5, where there is zero cumulative mass load, a pinch concentration exists. The pinch divides the overall network into two independent regions, *i.e.,* the regions above and below the pinch concentration. In the region above the pinch, mass load supplied by the water sources is completely consumed by the water sinks. On the other hand, excess mass load is found in the region below the pinch.

In order to achieve the water flowrate targets, water sources above the pinch (including fresh water) should neither be fed to the water sinks nor mixed with the water sources below the pinch. Various network design techniques are described in the literature for optimum design of water network *(1, 3, 7, 8, 9, 15)*. Note that WCA provides the baseline targets ahead of network design.

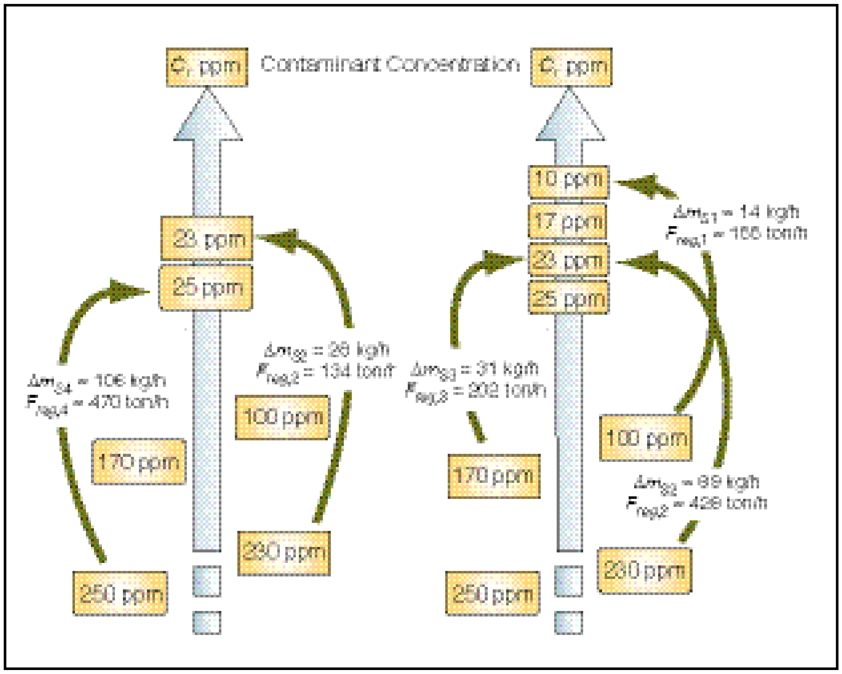
Combining the water cascade diagram with the interval water balance table yields the water cascade table (WCT) in Table 3. The key advantage of the WCT is that it enables a designer to clearly identify the pinch-causing stream(s) and the water-allocation targets. A pinch will always occur at the concentration level of a source*(10–12),* and is the point where the mass load supplied from the water sources just equals the load required by the water sinks.

In Table 3, a zero cumulative mass load at the concentration level of 230 ppm represents the pinch point. Hence, the pinch-causing stream that exists at this concentration level is the water source with a flowrate of 1,306 ton/h. Table 1 shows that this stream is a single water source, *i.e.,* the forming shower (S_2), or water spray.

In order to realize the pinch point and to achieve the MWR objective, a portion of the pinch-causing source stream (in this case, the forming shower) has to be allocated to the region above the pinch, while the rest goes to the region below the pinch. Referring to the cumulative net water source (F_C) column of Table 3, of the 1,306 ton/h water source from the forming shower, 1,236 ton/h (the interval between C_6 and C_7) must be sent to the region above the pinch (a negative sign indicates sending water across a driving force), while the remaining 70 ton/h (between C_7 and C_8) must be sent to the region below the pinch. These water allocation

Table 3. Water cascade balance for the paper mill example.

Level, k	Concentration (C_k), ppm	$\Sigma_j F_j$, ton/h	$\Sigma_i F_i$, ton/h	$\Sigma_j F_j - \Sigma_i F_i$, ton/h	F_C, ton/h	Mass Load, g/s,	Cumulative Mass Load, g/s
					F_{FW} = 848		
1	0			0			
					848	1,6962	
2	20	190		–190			1,6962
					658	3,9482	
3	80	831		–831			56,445
					–173	–3,462	
4	100	202	155	–46			52,983
					–220	–15,366	
5	170		202	202			37,617
					–18	–530	
6	200	1,219		–1,219			37,087
					–1,236	–37,087	
7	230		1,306	1,306			**0.00**
					70	1,391	**(PINCH)**
8	250		470	470			1,391
					F_{WW} = 539	539,226,029	
9	1,000,000						539,227,421



■ Figure 6. A regeneration unit can be installed to purify water sources..

flowrates can be verified with any detailed network design techniques, such as a source-sink mapping diagram *(9, 15)* or a sink-source allocation technique *(10, 13, 15).*

These important insights into the pinch-causing stream and water allocation are evident from the WCT, but are not available from other WPA graphical techniques (*e.g.*, Refs. 1, 2, 4, 10).

Optimizing the regeneration unit to achieve zero discharge

Water regeneration has been widely accepted as an effective means to further reduce water targets in WPA. Water regeneration involves the partial or total upgrading of water purity using any purification techniques. The regenerated water can either be reused in other water-using processes or recycled to the same process to further reduce fresh water and wastewater flowrates. In the context of WPA, regeneration above and across the pinch will reduce the fresh water and wastewater flowrates, while regeneration below the pinch will only reduce wastewater generation *(10, 12).*

Table 1 shows that the total flowrate of the water sinks is larger than that of the water sources. By regenerating all water sources to satisfy all water sinks, in principle, it is possible to completely eliminate wastewater and achieve a net fresh water demand of 309 ton/h.

In the paper mill water network, a regeneration unit can be placed either entirely above the pinch or across it, since both options will reduce the fresh water and wastewater flowrates. A dissolved air flotation (DAF) unit with a contaminant removal percentage (R) of 90% and an operating cost of \$0.50/kg of contaminant load removed will be con-

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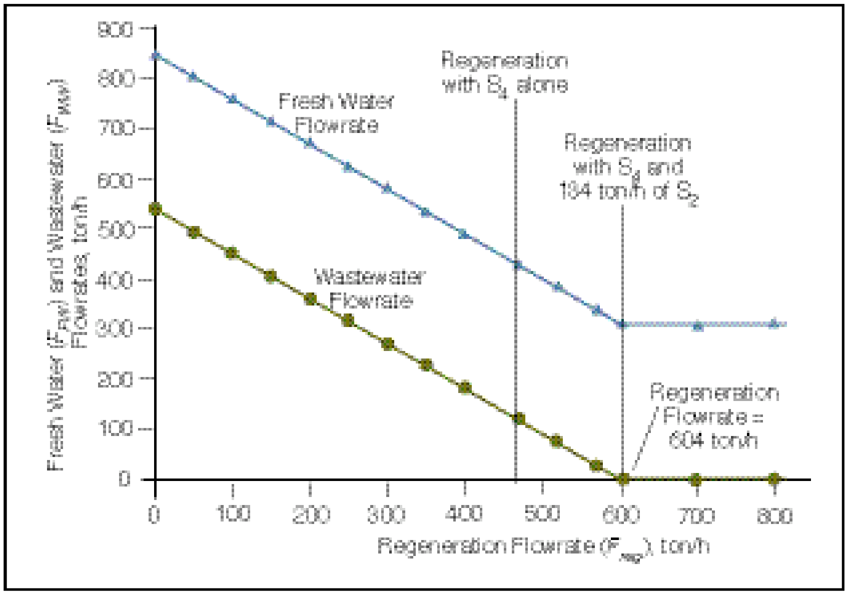

■ Figure 7. Fresh water and wastewater flowrates are a function of regeneration flowrate.

sidered. A DAF regenerates wastewater to a higher purity by introducing fine gas (usually air) bubbles that attach to and lift particles to the water surface for removal.

Any of the four water sources in Table 1 can be purified before reuse within the water network because the DAF unit is capable of regenerating these sources to the region above the pinch, which occurs at 230 ppm (Figure 5). For optimal regeneration, three key factors must be considered:

- selecting the optimal sequence to purify the available water sources
- deciding how much to purify each of the available water sources
- formulating the most cost-effective regeneration scheme.

The mass load removed from a water source i ($\Delta m_{S,i}$) in a regenerator is given by:

$$\Delta m_{S,i} = F_{R,i}\Delta C_R \qquad (3)$$

where $F_{R,i}$ is the flowrate and $\Delta C_R = C_{in} - C_{out}$ is the difference between the inlet and outlet concentrations of water source i. Since the operating cost is a linear function of the mass removed (Δm), the smaller the mass load removed from the water sources, the lower the operating costs of the regeneration unit will be.

Note also that, since the source flowrate ($F_{R,i}$) is inversely proportional to ΔC_R, a smaller $F_{R,i}$ would be required to regenerate a dirtier water source (larger ΔC_R) than for a cleaner water source (smaller ΔC_R) for a fixed amount of contaminant removed (Δm). For instance, for $R = 90\%$, a 250-ppm source needs to be purified to 25 ppm ($\Delta C_R = 225$ ppm), while a 100-ppm source needs to be purified to 10 ppm ($\Delta C_R = 90$ ppm).

Hence, to achieve zero discharge with the minimum capital and operating costs, the following heuristic is proposed:

Purify water sources one by one in descending order of concentration level.

This heuristic means that, in order to minimize the capital and operating costs, one should first purify the water source at the highest concentration level (or the "dirtiest"), and continue with sources at the next-highest concentration level until all water sources have been purified and wastewater eliminated to achieve zero discharge. Doing so will always lead to a smaller $F_{R,i}$ and, hence, a smaller total regeneration flowrate (F_{reg}), and ultimately smaller and less expensive equipment.

For the paper mill process, source S_4 is purified first, from 250 ppm to 25 ppm ($\Delta m_{S4} = 106$ kg/h, Figure 6a). This reduces the fresh water and wastewater flowrates to 429 ton/h and 121 ton/h, respectively, but this alone does not lead to zero discharge. Then, the next source, S_2, is purified from 230 ppm to 23 ppm ($\Delta m_{S2} = 28$ kg/h). This achieves zero liquid discharge.

The WCA procedure indicates that only 134 ton/h of S_2 ($F_{R,2}$) needs to be regenerated to achieve zero discharge. Knowing the exact regeneration flowrate is crucial to avoid excessive over-design and unnecessary capital expenditure. The fresh water target (F_{FW}) of 309 ton/h generated using WCA matches the target computed as the difference between the sum of water sources and the sum of water demands. The annual operating cost associated with the addition of DAF is approximately $533,800, calculated based on the total regeneration flowrate (F_{reg}) of 604 ton/h and total Δm removal of 133 kg/h.

Note that if one had started by purifying the cleanest water source, *i.e.*, S_1, first, followed by S_3 and S_2 (Figure 6b), the same annual operating cost of $533,800 (for the same amount of Δm removed) could be achieved. However, a larger F_{reg} of 785 ton/h, and hence a larger and more expensive DAF unit, would be needed to achieve zero discharge.

Figure 7 plots the fresh water and wastewater flowrates versus regeneration flowrate for the DAF unit, following the heuristic of purifying water sources in descending order. Note that fresh water being fed to the process remains constant at the regeneration flowrate of 604 ton/h. This is the turning point for the paper mill process to achieve zero liquid discharge.

One of the many possible water networks to achieve zero discharge is shown in Figure 8 and summarized in Table 4.

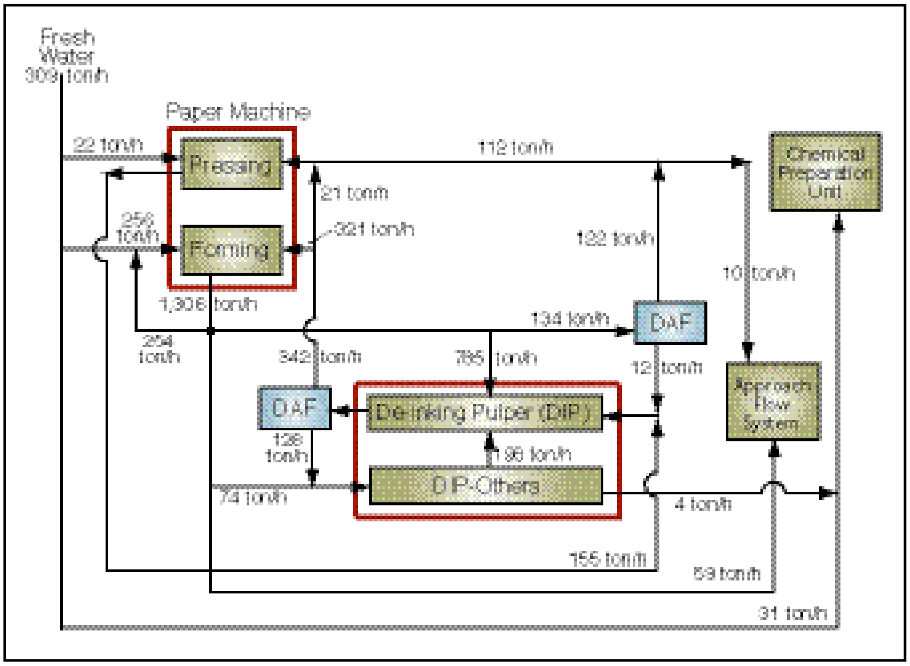

Figure 8. This water network achieves zero wastewater discharge for the paper mill example.

This network is more integrated than the original network in Figure 3 (in which most effluent water sources are sent for reuse and recycle). The water storage tank in the original network was removed and DAF units were installed to meet the inlet concentration of the water sinks. Apart from the total elimination of wastewater, the final network with regeneration achieves an 85% reduction in fresh water. This is an additional 27% reduction beyond reuse/recycle alone.

Closing thoughts

The systematic nature of WCA allows the technique to be automated and translated into any computer language for software development. WCA simplifies the task of incorporating the water surplus diagram *(10)* into computer software by eliminating the tedious iterative steps involved in constructing the diagram. WCA has been incorporated into *Water-MATRIX*, new software for flowrate targeting in water reuse/recycle developed by the Process Synthesis and Design Group, Dept. of Chemical Engineering, Universiti Teknologi Malaysia *(16)*. CEP

Table 4. Zero discharge network with DAF units.

Level, k	Concentration (C_k), ppm	$\Sigma_j F_j$, ton/h	$\Sigma_i F_i$, ton/h	$\Sigma_j F_j - \Sigma_i F_i$, ton/h	F_C, ton/h	Mass Load, g/s,	Cumulative Mass Load, g/s
					F_{FW} = 309		
1	0			0			
					309	6,175	
2	20	190		–190			6,175
					119	356	
3	23		134	134			6,531
					253	505	
4	25		470	470			7,037
					723	39,739	
5	80	831		–831			46,776
					–109	–2,172	
6	100	202	155	–46			44,604
					–155	–10,852	
7	170		202	202			33,752
					47	1,404	
8	200	1,219		–1,219			35,156
					–1,172	–35,152	
9	230		1,172	1,172			4
					F_{WW} = 0.00	–4	
10	1,000,000						**0.00 (PINCH)**

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