

## PROCESS DESIGN AND CONTROL

### Targeting Multiple Water Utilities Using Composite Curves

Sharifah Rafidah Wan Alwi\* and Zainuddin Abdul Manan\*

Chemical Engineering Department, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

The majority of techniques to determine the minimum water targets based on water pinch analysis (WPA) have assumed freshwater as the sole utility that exists at zero concentration. In practice, regenerated water and externally outsourced water such as rainwater, river water, snow, and imported spent water may exist at varieties of concentrations and can be used to reduce freshwater utility. This paper presents new procedures to establish the minimum flow rate targets for multiple water utilities using the source and sink composite curves. The work offers significant new insights into systematic placement of multiple new utilities through water outsourcing in the context of WPA.

#### 1. Introduction

The advent of water pinch analysis (WPA) as a tool for the design of an optimal water recovery network has been one of the most significant advances in the area of water conservation over the past decade.<sup>1–13</sup> Water pinch analysis is a systematic technique for implementing strategies to maximize water reuse and recycling through integration of water-using activities or processes. Maximizing water reuse and recycling can minimize freshwater consumption and wastewater generation.

Typical WPA solution comprises two steps, i.e., setting the minimum freshwater and wastewater flow rate targets followed by network design to achieve the targets. Graphical techniques such as the composite and grand composite curves and numerical techniques such as the problem table<sup>14</sup> and cascade analysis<sup>13</sup> have been used to determine the minimum utility targets and to locate pinch points in heat and water pinch analysis. In pinch heat analysis, the grand composite curve (GCC) has been a well-established tool for multiple utility placement. For WPA, Wang and Smith<sup>2</sup> have shown that varieties of freshwater sources, such as demineralized water, potable water, and borehole water may be available as utilities, and have used the limiting composite curve (LCC) shown in Figure 1 for placement of multiple water utilities at different concentrations for mass-transfer-based processes. Note that a process may employ either a single or multiple external water sources as utilities at a wide range of concentrations. This “outsourced water” may include rainwater, snow, borehole water, river water, and even “imported” spent water. Other works on multiple utilities targeting were presented by Gomes et al.<sup>15</sup> using a water source diagram (WSD), Foo<sup>16</sup> using water cascade analysis (WCA), and Almutlaq and El-Halwagi<sup>17</sup> using algebraic approaches. Other authors have considered freshwater as the sole water utility, with the vast majority assuming freshwater has zero concentration.

The limiting composite curves and water source diagram, however, are only ideal for cases where water-using processes are modeled as mass-transfer-based (MTB) operations involving

Table 1. Limiting Water Data from Polley and Polley<sup>6</sup>

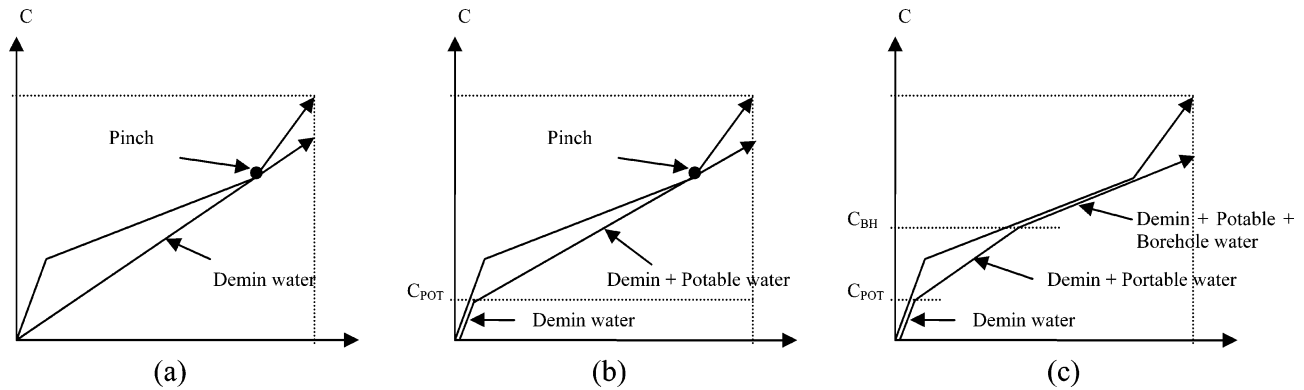
	<i>F</i> , t/h	<i>C</i> , ppm	<i>m</i> , kg/s	cum <i>F</i> , t/h	cum <i>m</i> , kg/s
demand					
D1	50	20	1	50	1
D2	100	50	5	150	6
D3	80	100	8	230	14
D4	70	200	14	300	28
source					
S1	50	50	2.5	50	2.5
S2	100	100	10	150	12.5
S3	70	150	10.5	220	23
S4	60	250	15	280	38

water as a lean stream or a mass separating agent (MSA). In an industrial project where flow rate gains and losses are quite common, it may be necessary to analyze these streams separately and modify the stream data as done by Liu et al.<sup>18</sup> if the MTB approach is used. A resilient tool should be able to handle not just MTB but also non-mass-transfer-based (NMTB) water-using operations involving flow rate gain or losses which include water used as a solvent or withdrawn as a product or a byproduct in a chemical reaction, or utilized as heating or cooling media. The water surplus diagram,<sup>11</sup> source and sink composite curves,<sup>12</sup> and water cascade analysis (WCA) techniques<sup>13</sup> fit the latter category and are well-established alternative methods used recently.

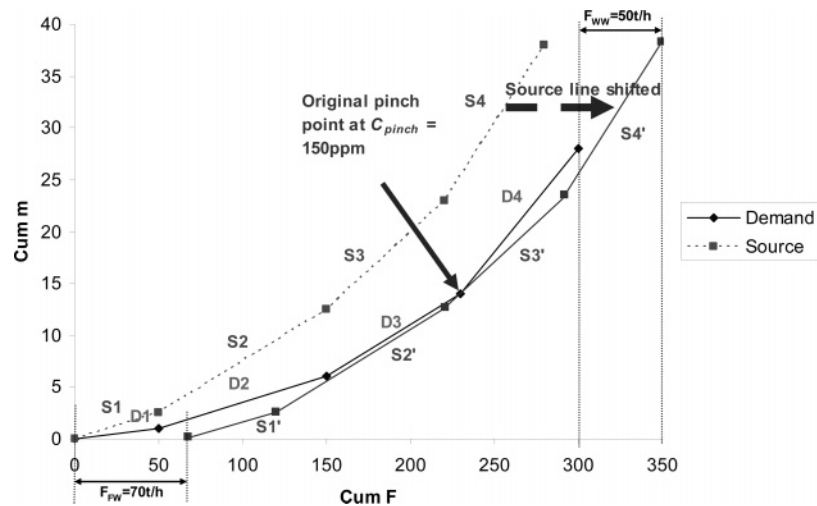
The water surplus diagram<sup>11</sup> is a grand composite curve used to target single freshwater utility and wastewater generation in WPA. The surplus diagram is applicable to MTB and NMTB operations and could handle all reuse, recycle, and mixing possibilities. The method, however, involves trial-and-error steps to find the pinch points and water targets and is only suited for targeting freshwater flow rate with zero concentration. El-Halwagi et al.<sup>12</sup> proposes source and sink composite curves (SSCC) as an alternative graphical utility targeting tool that eliminates the trial-and-error steps of surplus diagram and is also applicable to MTB and NMTB processes.

The SSCC is a plot of cumulative contaminant mass load (*y*-axis) versus cumulative flow rate (*x*-axis) of sources and demands arranged in ascending order of concentration. The source curve is then shifted along the zero mass load line until a pinch occurs and the source composite curve lies at or on the right of the demand composite curve. For example, the water

\* To whom correspondence should be addressed. Tel.: +60(07)-5536049 (S.R.W.A.); +60(07)-5535512 (Z.A.M.). Fax: +60(07)-5581463 (S.R.W.A., Z.A.M.). E-mail: shasha@fkkksa.utm.my (S.R.W.A.); zain@fkkksa.utm.my (Z.A.M.).



**Figure 1.** Wang and Smith<sup>2</sup> limiting composite curve to target multiple freshwater flow rates. (a) Target with the highest quality (demineralized) water. (b) Target with a mixture of high quality (demineralized) water and intermediate quality (potable) water. (c) Target with a mixture of high quality (demineralized) water, intermediate quality (potable) water, and low quality (borehole) water.



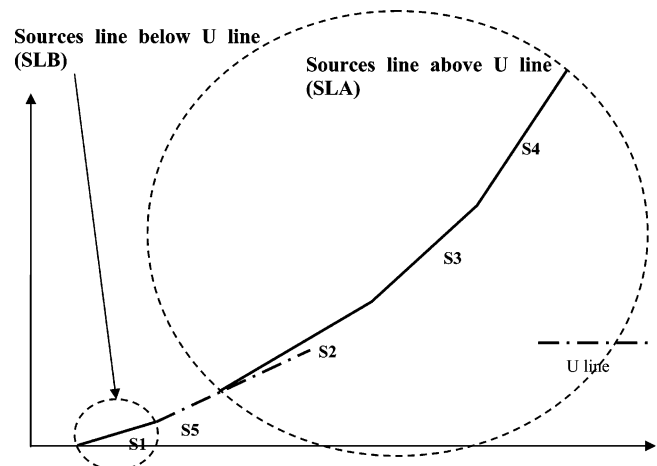
**Figure 2.** Water composite curves from the limiting data of Polley and Polley.<sup>6</sup>

demands and sources from the limiting data in Table 1<sup>6</sup> are first plotted beginning at the origin as shown in Figure 2. To get the minimum freshwater and wastewater flow rate targets, the entire source composite is shifted at zero mass load (assuming freshwater has zero concentration) until it touches the demand composite at the pinch point of the water composite curves (in this case, 150 ppm). The horizontal gap between the demand and source composites at zero mass load give the minimum freshwater flow rate (in this case, 70 t/h). The overshoot of the source composite gives the minimum wastewater flow rate (in this case, 50 t/h). The concentration of a stream on an SSCC can be obtained from its gradient. For example, the concentration of S2 shown in Figure 2 is

$$C_{S2} = \frac{12.5 \text{ kg/s} - 2.5 \text{ kg/s}}{220 \text{ t/h} - 120 \text{ t/h}} \times 1000 = 100 \text{ ppm}$$

Kazantzi and El-Halwagi<sup>19</sup> use SSCC to target a single fresh utility with nonzero concentration.

Manan et al.<sup>13</sup> introduce water cascade analysis (WCA), which is a numerical version of the NMTB grand composite (surplus diagram) by Hallale.<sup>11</sup> WCA allows the designer to rapidly and accurately generate the minimum water utility targets and water allocation targets, identify pinch-causing streams, and explore options and effects of process changes including regeneration. Foo<sup>16</sup> recently used the WCA technique to target multiple utilities. Manan et al.<sup>13</sup> pointed out that graphical and numerical approaches are complementary for targeting. A graphical approach is essential as a visualization tool and a numerical approach provides accurate targets.



**Figure 3.** Gaps in water pinch analysis research related to targeting multiple water utilities.

This paper describes a graphical SSCC procedure to determine the maximum limit for adding multiple water utilities and pure freshwater. This work complements the numerical approaches of Foo<sup>16</sup> and Almutlaq and El-Halwagi.<sup>17</sup> The maximum limit for adding multiple water utilities is referred to in this work as the minimum utility flow rate ( $F_{MU}$ ). Note that  $F_{MU}$  results in the minimum freshwater flow rate,  $F_{FWU}$ . In this work,  $F_{FWU}$  as a conventional water utility will be clearly distinguished from outsourced utilities ( $F_{MU}$ ).  $F_{MU}$  is an external (outsourced) water utility with nonzero concentration.  $F_{FWU}$  refers to a pure

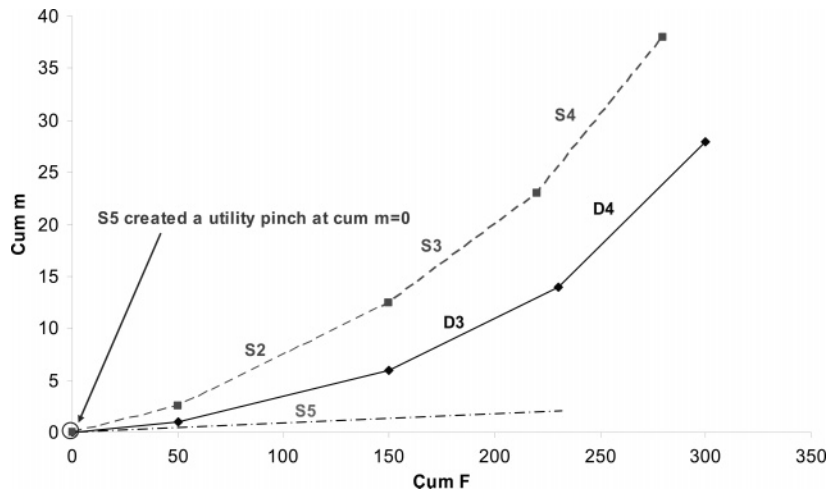


Figure 4. Location of various water sources relative to the utility line S5.

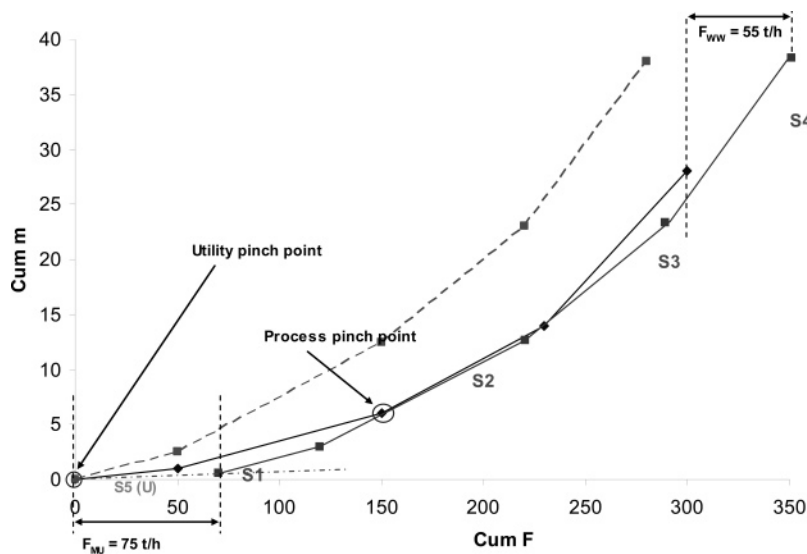


Figure 5. Utility line (S5) creating a utility pinch.

freshwater source at 0 ppm concentration. Kazantzi and El-Halwagi<sup>19</sup> used SSCC to target a single impure fresh source. However, they did not consider concentration-based problems and cases where both pure fresh ( $F_{FWU}$ ) and multiple impure utility sources ( $F_{MU}$ ) are involved, as covered in this work.

This work offers significant new insights into systematic placement of single and multiple new utilities involving water outsourcing. This work assumes higher quality utilities to be more expensive and should therefore be minimized in favor of lower quality utilities. The method is currently applicable to single-contaminant systems. The new contribution that has emerged from this work is the establishment of a new procedure and a set of new heuristics to use SSCC to determine the minimum flow rate targets for multiple water utilities at various concentrations.

Section 2 describes the systematic technique to determine targets for a single utility and pure freshwater for pinch and threshold problems using source and sink composite curves. Section 3 presents the technique to set targets for multiple new utilities using source and sink composite curves.

## 2. Targeting the Minimum Flow Rate for a Single Utility Using Water Composite Curves

The current SSCC technique can only target the minimum flow rate for a single utility freshwater ( $F_{FWU}$ ) which exists at

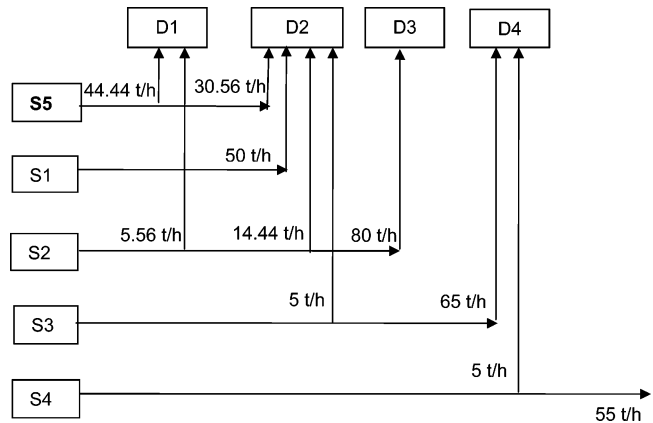


Figure 6. SLA shifted along S5. Final composite curve with minimum utility addition.

zero concentration<sup>12</sup> and nonzero concentration.<sup>19</sup> This section explains how the SSCC could be used to determine the  $F_{MU}$  for a single utility and, at the same time, the minimum pure freshwater target ( $F_{FWU}$ ). The section is divided into pinched and threshold problems to evaluate different cases.

**Pinched Problems.** Prior to determining the minimum new utilities flow rate ( $F_{MU}$ ), it is important to establish if a utility is suitable for a given process using the following heuristic:

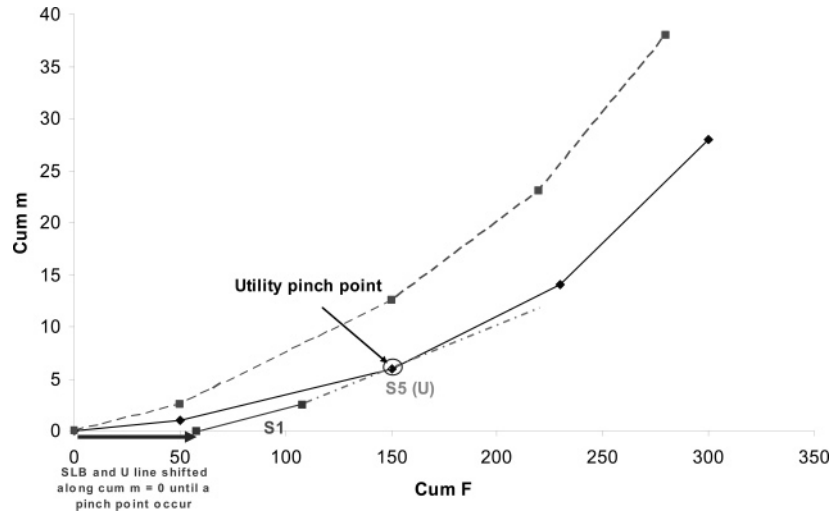


Figure 7. SLB (S1) and S5 shifted along the cum  $m = 0$  line.

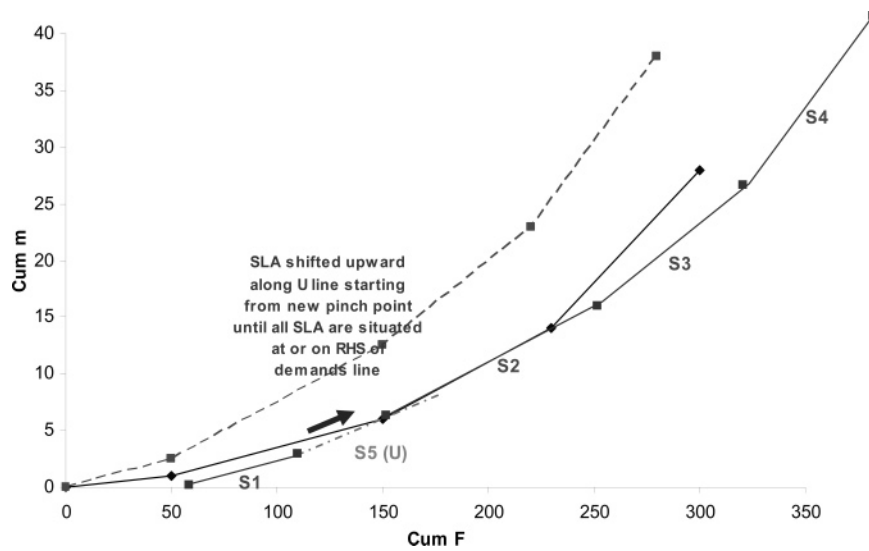


Figure 8. SLA (S2–S4) shifted upward along S5 from the new pinch point until SLA created another pinch point at  $C_{pinch} = 100$  ppm.

Table 2. Limiting Data for Example 3

	$F$ , t/h	$C$ , ppm	$m$ , kg/s	cum $F$ , t/h	cum $m$ , kg/s
demand					
D1	10	0	0	10	0
D2	120	5	0.6	130	0.6
D3	50	30	1.5	180	2.1
D4	80	40	3.2	260	5.3
D5	50	50	2.5	310	7.8
D6	30	100	3	340	10.8
D7	90	150	13.5	430	24.3
source					
S1	10	10	0.1	10	0.1
S2	70	50	3.5	80	3.6
S3	80	100	8	160	11.6
S4	50	200	10	210	21.6
S5	30	300	9	240	30.6
S6	90	500	45	330	75.6

Heuristic 1: Only consider a water source as utility if its concentration is lower than the concentration of the pinch.

A utility at a concentration higher than the pinch point will only increase wastewater. Say that a water source at a concentration lower than the pinch is available for the limiting data in Table 1. The  $F_{MU}$  can be obtained by systematically moving the source line above (SLA) along the utility line ( $U$ ) and the source line below (SLB) until utilities/process pinches are obtained. The  $U$  locus is the line with a slope of the utility concentration forming the path along which SLA/SLB is shifted.

Figure 3 illustrates the locations of source lines above (SLA) and below (SLB) and the  $U$ . A utility pinch is a pinch point created by a utility line intersecting a demand composite curve. A process pinch, on the other hand, is a pinch point created by the intersection of the source composite curve and demand composite curve.

Systematic shifting of SLA and SLB to get  $F_{MU}$  involves two key steps:

1. To target the minimum pure freshwater ( $F_{FWU}$ ), move the utility line along with SLB to the right-hand side of the demand

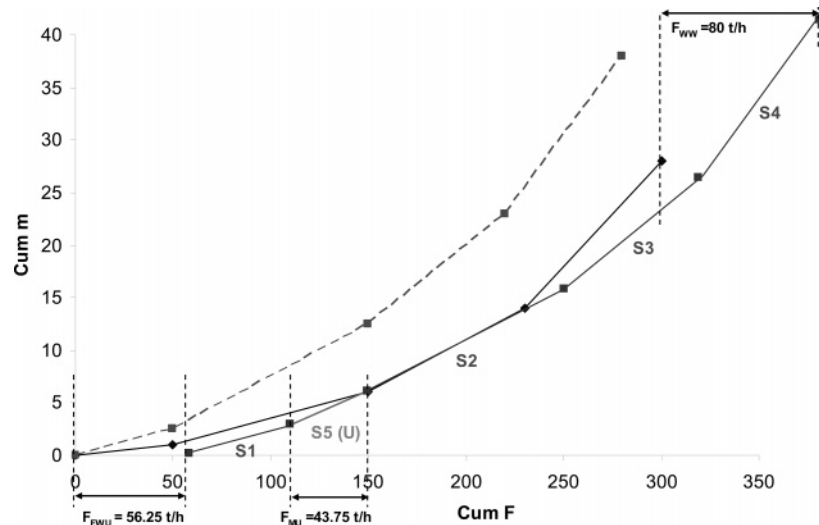


Figure 9. Final composite curves with addition of S5.

composite until the line meets either the first utility or process pinch (SLB and utility lines must pinch the demand composite).

2. To target the maximum limit of outsourced utility ( $F_{MU}$ ), shift SLA upward along the utility line until the entire SLA pinches the demand composite.

The systematic shifting of SLA and SLB along the  $U$  line will be illustrated using four different examples.

(i) Example 1: A utility has no SLB and creates a utility pinch.

S5 at a concentration of 10 ppm is a utility added to the limiting water data from Polley and Polley.<sup>6</sup> There is no water source below S5. Hence, the S5 line is drawn first and shifted until a utility pinch ( $C_{pinch} = 10$  ppm) occurs at  $cum\ m = 0$  according to step 1 (Figure 4).

SLA (S1–S4) is moved upward according to step 2 along the S5 until a process pinch occurs at  $C_{pinch} = 150$  ppm (Figure 5). The horizontal gap between the demand composite and the intersection of SLA and S5 gives the minimum utility flow rate ( $F_{MU}$ ), i.e., 75 t/h, and no  $F_{FWU}$  is needed. Figure 6 shows the possible water network design that achieved the target for Example 1. Note that all the designs in this work were produced using the network design guidelines reported by Polley and Polley<sup>6</sup> and Hallale.<sup>11</sup>

(ii) Example 2: A utility has an SLB and creates a utility pinch.

S5 is a utility at 80 ppm added to the limiting data from Polley and Polley.<sup>6</sup> Shifting SLB (S1) and S5 along the zero “Cum  $m$ ” axis according to step 1 creates a utility pinch at  $C_{pinch} = 80$  ppm (Figure 7). SLA (S2–S4) is next shifted according to step 2 along S5 from the new pinch point onward until a process pinch point is created at  $C_{pinch} = 100$  ppm (Figure 8). Figure 9 shows the final composite curves with  $F_{MU}$  of 43.75 t/h and  $F_{FWU}$  of 56.25 t/h. Figure 10 shows the possible water network design that achieved the target for Example 2.

(iii) Example 3: Utility addition does not create a utility pinch.

Table 2 shows the limiting data for example 3. S7 is a utility added at 130 ppm. Note that, unlike in the previous examples, shifting S7 and SLB in this case created a process pinch at  $C_{pinch} = 100$  ppm instead of a utility pinch. Figure 11 shows the final composite curves after shifting S7 and SLB along the zero “Cum  $m$ ” axis line and after moving SLA upward from the process pinch along S7. The  $F_{MU}$  for this case is 52.9 t/h. The process pinch points are at 100 ppm (on line S3) and 200 ppm (on line S4). The pure freshwater and wastewater targets are 188.0 and

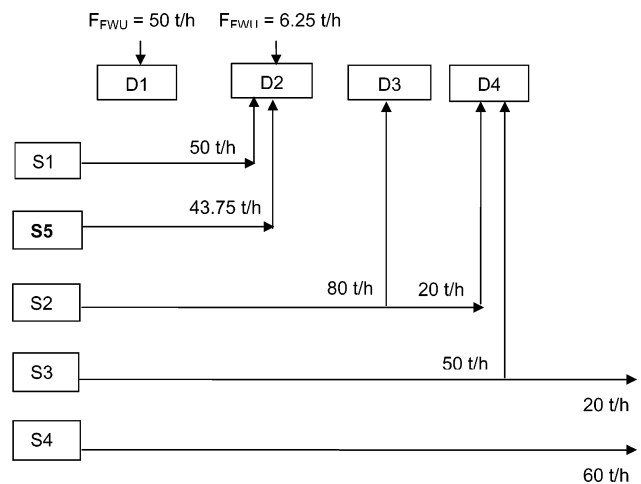


Figure 10. Composite curves with utility (S7) addition.

140.9 t/h, respectively. Figure 12 shows the possible water network design that achieved the target for Example 3.

**Threshold Problem.** A process that has either freshwater or wastewater as a “utility” is a threshold problem. This example (example 4) focuses on a threshold problem that does not produce wastewater. Foo<sup>20</sup> presents the WCA approach for targeting freshwater for a threshold problem. Next, we demonstrate that the graphical SSCC targeting approach can also be applied for threshold problems.

Note that since the flow rate of regenerated source equals the flow rate of reduced wastewater source, regeneration would not change the flow rate of freshwater and wastewater for this case. Harvesting external water source provides more room for savings and is therefore the more preferred option. For this type of threshold problem, a pinch may or may not exist. If a pinch exists, the utility targeting technique for a pinch problem applies. For a threshold problem without a pinch point, the following steps should be taken:

1. Shift the utility line with the SLB until a utility/process pinch point is created.

2. Shift the SLA (S3) above the utility/process pinch point upward along the utility line and the SLB until all demand flow rates are satisfied.

(iv) Example 4: Threshold problem, one new utility (U1) at 80 ppm.

Table 3 is the limiting data for example 4, and Figure 13 is

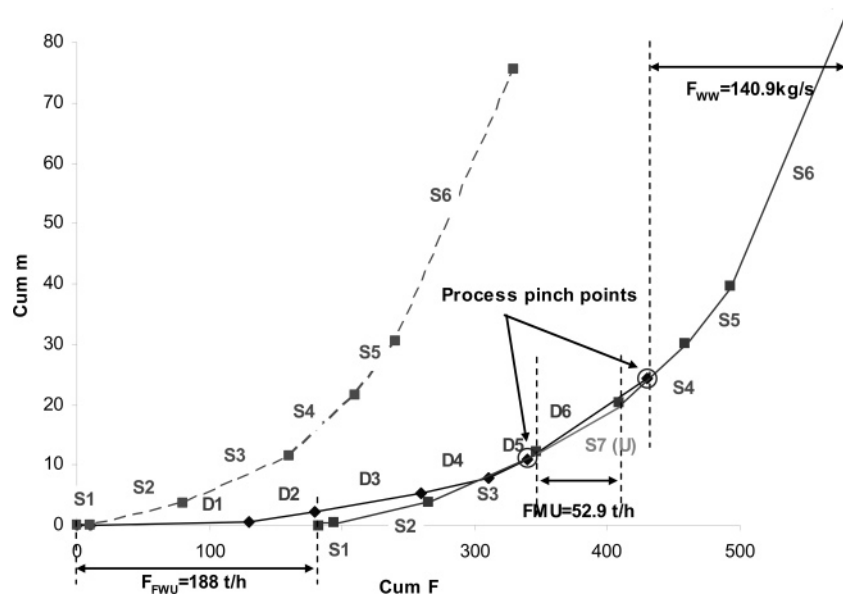


Figure 11. Water composite curves for example 4: a threshold problem.

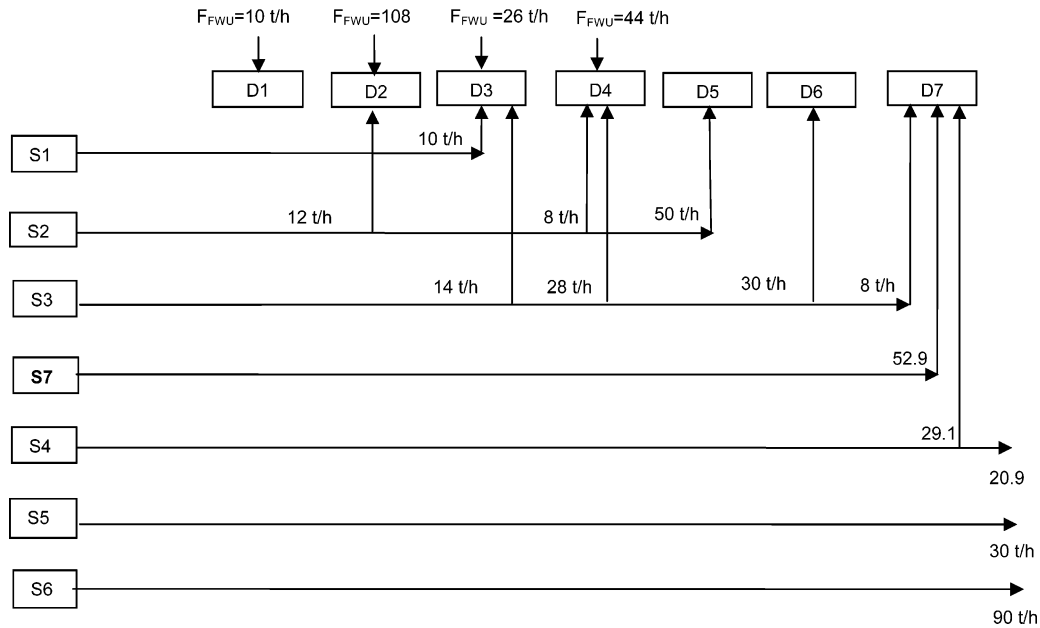


Figure 12. Composite curves for threshold problem with addition of S4 utility.

Table 3. Limiting Data for Threshold Problem (Example 4)

	$F$ , t/h	$C$ , ppm	$m$ , kg/s	cum $F$ , t/h	cum $m$ , kg/s
demand					
D1	10	0	0	10	0
D2	120	5	0.6	130	0.6
D3	130	10	1.3	260	1.9
D4	50	50	2.5	310	4.4
D5	30	100	3	340	7.4
D6	90	200	18	430	25.4
source					
S1	10	10	0.1	10	0.1
S2	70	50	3.5	80	3.6
S3	80	100	8	160	11.6

the corresponding initial composite curves for a threshold problem. The initial freshwater target is 269.99 t/h. The utility line (S4) at 80 ppm is added and shifted with the SLB (S1 and S2) to the right of the demand composite until a pinch point occurs at  $C_{pinch} = 80$  ppm. The SLA (S3) above the utility pinch

point is shifted upward along the S4 until the water demand flow rates are fully satisfied (see Figure 14). The  $F_{MU}$  for this case is 50 t/h, and the pinch point is at 80 ppm. The new pure freshwater target is 220 t/h. Figure 15 shows the possible water network design that achieved the target for Example 4.

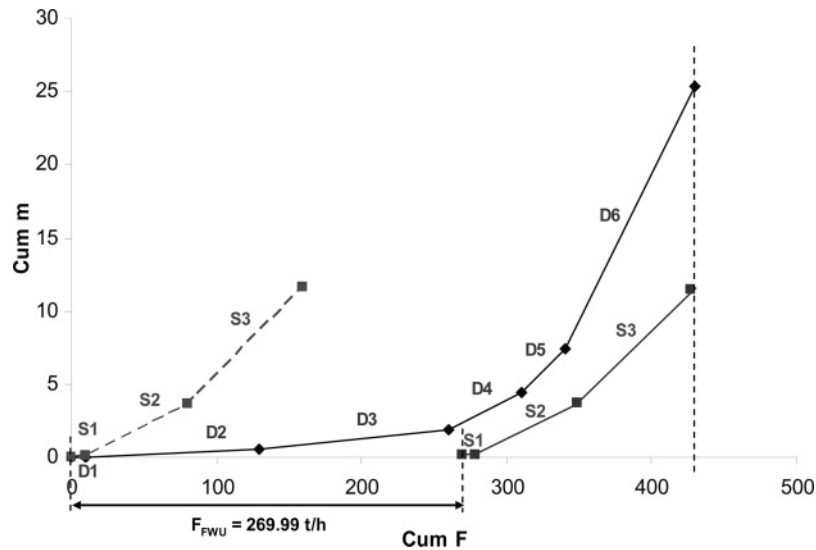


Figure 13. Water composites with addition of U1 (S5) at  $C = 10$  ppm.

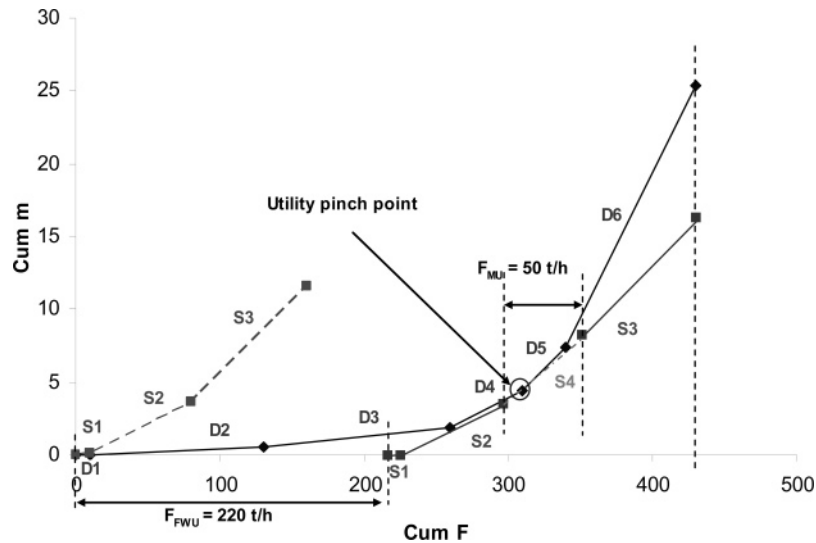


Figure 14. Shifting of SLB and U2 line ( $C = 80$  ppm) along U1 ( $C = 10$  ppm) line until a pinch point occurred.

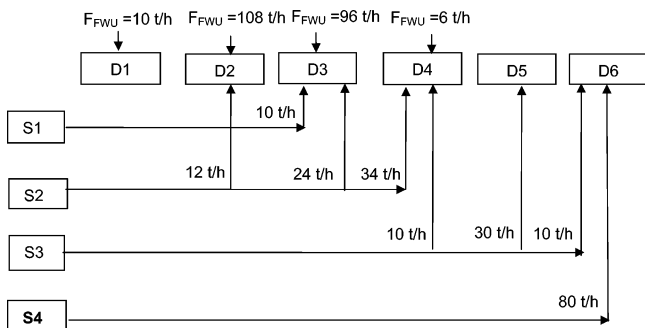


Figure 15. Final water composites after addition of U1 and U2.

### 3. Targeting Multiple $F_{MU}$ Values Using Source and Sink Composite Curves

Now that we know how to target for a single utilities minimum flow rate ( $F_{MU}$ ) and a minimum pure freshwater flow rate ( $F_{FWU}$ ) using source and sink composite curves (SSCC), we will proceed to explain how a minimum multiple utility flow rate can be determined.

A higher quality (cleaner) utility is usually more valuable particularly for cases involving regeneration. Thus, when multiple sources of water and regenerated wastewater are available as utilities, the general rule is to minimize the use of

higher quality utility in order to maximize savings. This could be achieved using the following heuristic:

Heuristic 2: *Using water composite curves, obtain the  $F_{MU}$  values one by one, starting from the cleanest to the dirtiest water source.*

Heuristic 2 means that the  $F_{MU}$  for the cleanest *new utility* must be obtained first using the composite curves procedure described. Adding a utility will create new utility and process pinch points. The next utility could only be considered if its concentration is lower than the highest pinch concentration. Note that the maximum utility freshwater savings had already been reached with the addition of the first utility. Therefore, addition of a dirtier utility should only reduce the flow rate of the cleaner utility added previously. The same procedure is repeated until all available utilities have been utilized. Example 5 explains how the technique was implemented.

(iv) Example 5: Two new utilities are included: U1 at 10 ppm and U2 at 80 ppm.

To illustrate the technique, the limiting data from Polley and Polley<sup>6</sup> are assessed for possible integration with two new utilities, U1 and U2, available at 10 and 80 ppm, respectively. Note that U1 is S5 from example 1. U1 as the cleaner utility at 10 ppm is considered first according to heuristic 1. Figure 6 shows that the  $F_{MU1}$  for S5 is 75 t/h and the utility and process

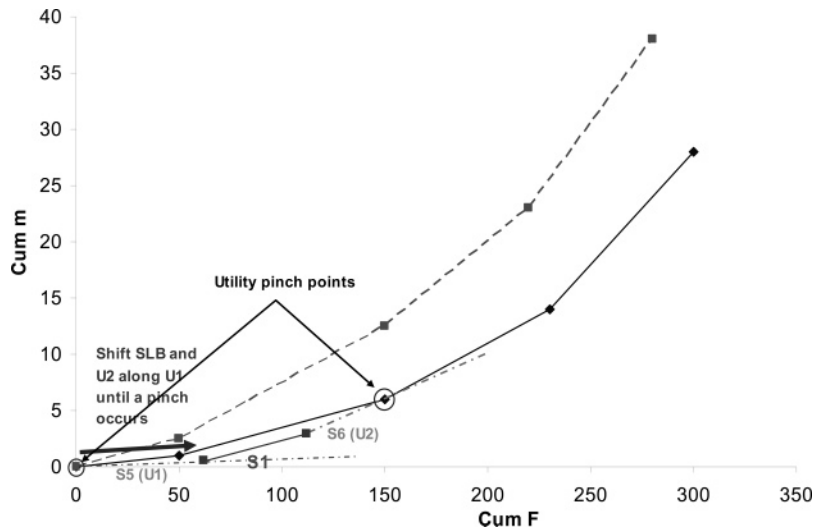


Figure 16. Possible network design for examples 1 and 2.

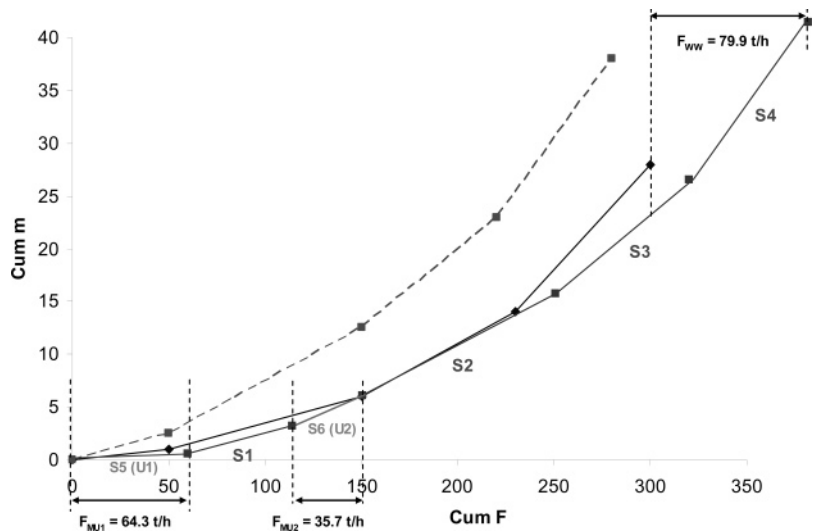


Figure 17. Possible network design for example 3.

pinches are at 0 and 100 ppm. U2 (S6) at 80 ppm is a viable utility since it existed below the new pinch point at 100 ppm. S6 is drawn next and shifted with SLB (S1) downward along the first utility line (S5) until another utility pinch occurs at 80 ppm (see Figure 16). Next, the SLA above S6, i.e., S2–S4, was drawn at the new utility pinch of 80 ppm and shifted until it completely appeared on the right-hand side of the demand composite, or until it created a new pinch point. This gave  $F_{MU1}$  and  $F_{MU2}$  of 64.3 and 35.7 t/h, respectively (Figure 17). The multiple utility targeting procedures ultimately yielded pure freshwater and wastewater targets at 0 and 79.9 t/h, respectively. Note that if SLA had created a new process pinch when it was shifted along S6, any new water source at concentration lower than the new process pinch point could still be added to further reduce S6. Figure 18 shows the possible water network design that achieved the target for Example 5.

Comparing the results of using two new utilities (Example 5) with the results of using only one new utility (example 1), it can be seen that the former yields the same  $F_{FWU}$  target as in the case of only one utility (example 1), i.e., 0 t/h. However, Example 5 achieves  $F_{MU1}$  and  $F_{MU2}$  values of 64.3 t/h and 35.7 t/h, respectively, whereas example 1 achieves a  $F_{MU}$  value of 75 t/h. Considering only the total flow rate of the utility, Example 1 clearly yields the better solution. However, since

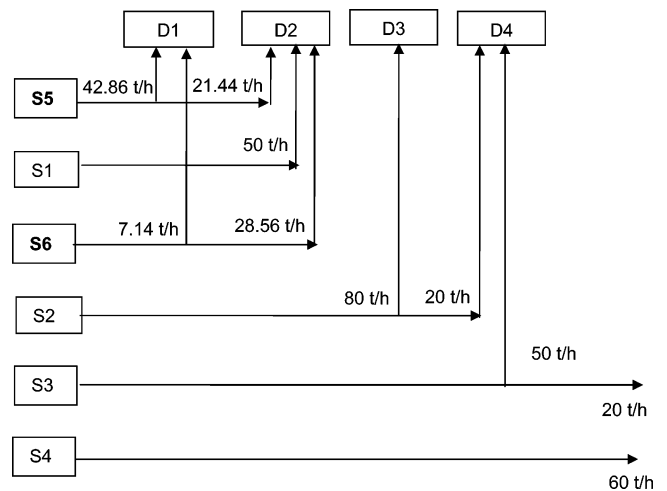


Figure 18. Possible network design for examples 4 and 5.

this work assumes higher-quality utilities to be more expensive, the higher-quality utility should therefore be minimized in favor of lower-quality utilities. The best option, in terms of economy, can be more conclusively determined by conducting a more-detailed economic analysis.



#### 4. Conclusion

Systematic procedures to establish the minimum flow rate targets for a single utility and multiple utilities using source and sink water composite curves (SSCC) have been developed. This latest development provides a generic graphical technique for setting the minimum flow rate targets involving multiple sources of water utilities. Design of the water recovery network that achieves the target can be done by using established techniques such as a source and sink mapping diagram by Polley and Polley.<sup>6</sup> The minimum utility flow rate ( $F_{MU}$ ) represents the maximum pure freshwater ( $F_{FWU}$ ) savings and the limit for adding utilities through water outsourcing. Several new rules and heuristics have been established to guide the placement of utilities and ensure maximum water savings. The water composite curve is the preferred tool as it provides significant insights on how the minimum new utility flow rates ( $F_{MU}$ ) are determined and why the reduction occurs.

#### Nomenclature

##### Symbols

$C$  = concentration

cum = cumulative

$D$  = demand

$F$  = flow rate

t/h = metric tons per hour

$m$  = mass load

NU = new utility

$P$  = purity

ppm = parts per million

$S$  = Source

SLA = sources line after new water source line

SLB = sources line before new water source line

$U$  = utility

##### Subscripts

FW = freshwater

FWU = freshwater utility

max = maximum

MU = minimum utility

WW = wastewater

#### Literature Cited

(1) Wang, Y. P.; Smith, R. Wastewater Minimisation. *Chem. Eng. Sci.* **1994**, *49*, 981–1006.

(2) Wang, Y. P.; Smith, R. Wastewater minimisation with flowrate constraints. *Trans. Inst. Chem. Eng., Part A* **1995**, *73*, 889–904.

(3) Olesen, S. G.; Polley, G. T. A simple methodology for the design of water networks handling single contaminants. *Trans. Inst. Chem. Eng., Part A* **1997**, *75*, 420–426.

(4) Dhole, V. R.; Ramchandani, N.; Tainsh, R. A.; Wasilewski, M. Make your process water pay for itself. *Chem. Eng.* **1996**, *103*, 100–103.

(5) Sorin, M.; Bédard, S. The global pinch point in water reuse networks. *Trans. Inst. Chem. Eng., Part B* **1999**, *77*, 305–308.

(6) Polley, G. T.; Polley, H. L. Design better water networks. *Chem. Eng. Prog.* **2000**, *96* (2), 47–52.

(7) Prakash, R.; Shenoy, U. V. Targeting and design of water networks for fixed flowrate and fixed contaminant load operations. *Chem. Eng. Sci.* **2005**, *60* (1), 255–268.

(8) Mann, J. G.; Liu, Y. A. *Industrial Water Reuse and Wastewater Minimization*; McGraw-Hill: New York, 1999.

(9) Feng, X.; Seider, W. D. New structure and design method for water networks. *Ind. Eng. Chem. Res.* **2001**, *40*, 6140–6146.

(10) Dunn, R. F.; Wenzel, H. Process integration design methods for water conservation and wastewater reduction in industry. Part 1: Design for single contaminant. *Clean Prod. Process.* **2001**, *3*, 307–318.

(11) Hallale, N. A new graphical targeting method for water minimization. *Adv. Environ. Res.* **2002**, *6* (3), 377–390.

(12) El-Halwagi, M. M.; Gabriel, F.; Harrel, D. Rigorous graphical targeting for resource conservation via material reuse/recycle networks. *Ind. Eng. Chem. Res.* **2003**, *42*, 4319–4328.

(13) Manan, Z. A.; Tan, Y. L.; Foo, D. C. Y. Targeting the minimum water flowrate using water cascade analysis technique. *AIChE J.* **2004**, *50* (12), 3169–3183.

(14) Linnhoff, B.; Townsend, D. W.; Boland, D.; Hewitt, G. F.; Thomas, B. E. A.; Guy, A. R.; Marshall, R. H. *A User Guide on Process Integration for the Efficient Use of Energy*; Institution of Chemical Engineers: Rugby, U.K., 1982.

(15) Gomes, J. F. S.; Queiroz, E. M.; Pessoa, F. L. P. Design Procedure for water/wastewater minimization: single contaminant. *J. Clean. Prod.* **2007**, *15*, 474–485.

(16) Foo, D. C. Y. Water Cascade Analysis for Single and Multiple Impure Fresh Water Feed. *Chem. Eng. Res. Des.* **2007**, *85* (A8), 1–9.

(17) Almutlaq, A. M.; El-Halwagi, M. M. An Algebraic Targeting Approach to Resource Conservation via Material Recycle/Reuse. *Int. J. Environ. Pollut.* **2007**, *29* (1/2/3), 4–18.

(18) Liu, Y. A.; Lucas, B.; Mann, J. Up-to-date Tools for Water-System Optimization. *Chem. Eng. Mag.* **2004**, *1*, 30–41.

(19) Kazantzi, V.; El-Halwagi, M. M. Targeting Material Reuse via Property Integration. *Chem. Eng. Prog.* **2005**, *101* (8), 28.

(20) Foo, D. C. Y. Flowrate Targeting for Threshold Problems and Plant-Wide Integration for Water Network Synthesis. *J. Environ. Manage.* **2007**, in press. (DOI: 10.1016/j.jenvman.2007.02.007.)

Received for review September 21, 2006

Revised manuscript received June 6, 2007

Accepted June 11, 2007

IE061238K