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Total Site Water Main Concentration Selection: A Case Study

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A water main is an interface between water sources and sinks to reduce the complexity of the Total Site Integration for water reuse. The selection of the contaminant concentration of water main can significantly affect the site freshwater use and wastewater generation. This paper proposes a hierarchical approach to the selection of the inter-plant water main concentration for minimising the water utilities. The algorithm first performs Plant-Level Water Integration, exposing to the site level only the residual water sources and sinks. The case study shows that, for the water main inlet concentration increase from 100 ppm to 800 ppm, the minimum freshwater input increases from 127.5 t/h to 133.3 t/h, and the wastewater generation increases from 132.5 to 138.4 t/h. The trend, in this case, can be explained by the fact that the water sinks require cleaner water than the water main can offer. The conclusion is that the selection of the water main contaminant concentration requires balancing the availability from water sources and the demand by water sinks at the site level.

1. Introduction

Water scarcity has become a serious global issue, and the industry is a major water consumer. Energy production and manufacturing industry account for 39 % of the total water use in Europe (EEA, 2020), taking into account that parts of the manufacturing industry have been relocated to Asia. Improving water reuse and reducing wastewater discharge is the key to mitigate the issue. The industry has a high potential for water reuse and efficiency improvement via Water Integration and water reuse. Process Integration for water minimisation has been initiated by Wang and Smith (1994) and has been considerably developed. Manan et al. (2009) proposed a method for designing effective water networks involving multiple contaminants using mathematical optimisation. Zhao et al. (2018) proposed a design method of a Water-Heat Integrated network with multiple contaminants.

Based on the Pinch Analysis targeting of minimum freshwater inside plants, Inter-Plant Water Integration was first addressed by Olesen and Polley (1996), accounting for topology and piping constraints. Total Site Water Integration has been previously investigated, but the complex water networks from superstructure optimisation can be costly and less favourable for implementation (Klemeš et al., 2018). Indirect Inter-Plant Water Integration via a centralised hub (Chew et al., 2008) was then investigated. Water networks with internal water main (single contaminant) were first introduced by Feng and Seider (2001) and were then modified to cover multiple contaminants (Wang et al., 2003).

The application is expanded to interplant networks with mains for water reuse and regeneration (Cao et al., 2004). Water network designs with simplified structure have been proposed to improve controllability and operational flexibility (Cao et al., 2004). Chen et al. (2010) proposed a mathematical model for the design of inter-plant water networks with central and decentralised water mains, where water mains are places to serve as buffers between different processes. In their study, all the water-using units of the individual plants are interconnected via central and decentralised water mains. Fadzil et al. (2018) proposed the U-shaped two-way centralised water reuse header to improve the water reuse network, and the results showed that the installation could reduce 56.2 % of the freshwater input and 55.9 % of wastewater generation. The number of headers and

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the inlet limiting concentrations of these headers are pre-set at 150 ppm by selecting the concentration limit required by most of the water-using processes based on the extracted data (Fadzil et al., 2018).
In the existing inter-plant water main studies, all water-using units of each plant are interconnected via the water main, and no direct intra-plant water reuse is considered. This could increase the complexity of the total site water network and the cost of piping, as distances between different plants are normally longer than within individual plants (Chew et al., 2008). Another research gap is that the selection of water main concentrations has not been well investigated, as most of the studies pre-set the water main concentration. It is still a challenge to allocate the inlet concentration levels of water main at the site level. This study proposes a general procedure to select the inter-plant water main concentration. The procedure considers two integration levels: Intra-Plant Integration and Inter-Plant Integration of the residual site water sources and sinks.

2. Method

2.1 Problem statement

Given a total site of n plants with i water-using units in each plant (the value of i can differ within each plant), and a single contaminant is considered. Water reuse main is introduced to the site, and the wastewater main is used to collect effluents that are not able to be reused within site and send to wastewater treatment. Freshwater at 0 ppm is the only external water source. The objective is to select the inlet concentration of the inter-plant water main that achieves minimum firewater consumption and wastewater generation.

2.2 Inter-plant water main selection

A six-step approach is proposed in this study to select the inter-plant water main concentration, as illustrated in Figure 1a. The first step is to target the maximum water reuse within each plant using Water Surplus Diagram (Hallale, 2002). This aims at minimising piping distances inside the plant. The excess source flows are then extracted from each plant as candidates to be sent to the site water reuse main (Step 2). In Step 3, each concentration of the extracted flow is set as the potential water main inlet concentration, which allows source flows lower than this value to enter the water main, and those with higher concentration are sent to wastewater treatment. After mixing the selected site water sources, the resulting water from the main has a concentration equal to or lower than the specified level and can be sent to the site water sinks. In Step 4, with each selection, the outlet flowrate and outlet concentration of the water main is calculated. In Step 5, the water main outflow is used as the additional source flow to each plant to calculate the minimum freshwater flowrate and wastewater generation.

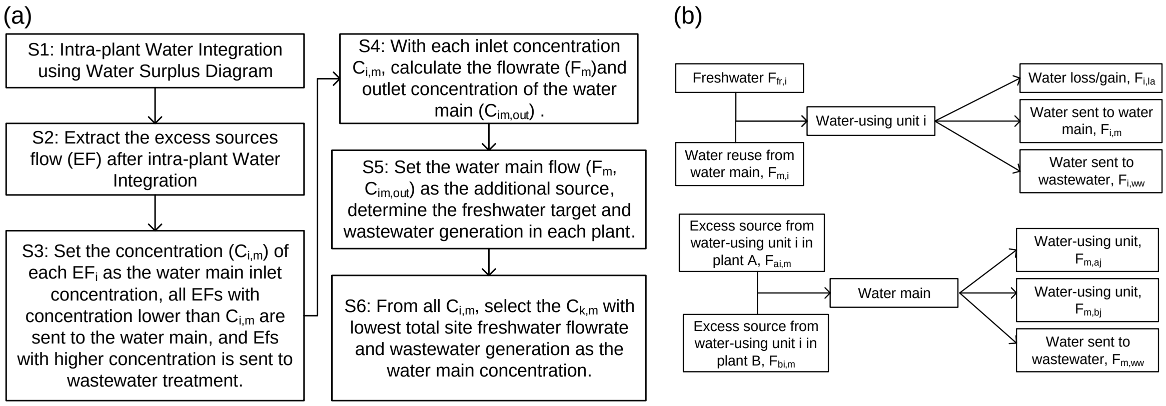

Figure 1a: Procedure of inter-plant water main selection, b: Superstructure of a water-using unit and water main

In the last step, the water main inlet concentration is selected from the scenario with minimum freshwater demand for the site.

2.3 Water Surplus Diagram

The Water Surplus Diagram (WSD) (Hallale, 2002) is a useful graphical tool for freshwater targeting. To plot the WSD, the Water Source and Sink Composite Curves have to be plotted first based on the given limiting data. The areas of the rectangles shaped by the two Composite Curves can be calculated to construct the WSD. Note that an initial freshwater flowrate should be assumed and included in the Source Curve, and the freshwater target can be determined by adjusting the freshwater flowrate value. The Composite Curves clearly present the water surplus and deficit, and the WSD can determine the minimum freshwater considering the mixing of two sources (Hallale, 2002). In this study, the WSD has been slightly adjusted for better illustration. For example, contaminant concentration is used in the y-axis instead of the purity levels in the original work (Hallale, 2002). The calculated areas represent the excess impurity capacity (when positive) or extra impurity load (when negative), so the mass load is used as the x-axis instead of flowrate (Foo, 2009).

2.4 Mass balance in the inter-plant water main

As illustrated in Figure 1a, before implementing Inter-Plant Water Integration, each plant has to reach maximum intra-plant water reuse. Only excess source flows above the Pinch Point are sent to the site water main. After full mixing of all site water sources, the outflow of the water main is sent to sinks which require concentration equal to or higher than the outlet concentration of the water main. For each water-using unit i, the water sources can be freshwater or the reused water from the site water main. In this study, the water main accepts water flows at a concentration equal or lower than its inlet concentration, and sends the water to water sinks requires concentration equal or higher than the outlet concentration of the water main (Feng and Seider, 2001). Other flows with higher concentration would be directly sent to wastewater. For example, when the inlet concentration is set as 50 ppm, all eligible sources with concentration less than 50 ppm are sent to the water main, and sources with higher than 50 ppm are sent to wastewater for discharge. As illustrated in Figure 1b, the balance of the water main is:

$$F_{ai,\mathrm{m}} + F_{ai,m} = F_{m,aj} + \mathrm{F}_{m,bj} + F_{m,ww} \tag{1}$$

Where F denotes the water flow rate (t/h), subscript i represents the water-using units i. $F_{ai,m}$ and $F_{bi,m}$ represent the inlet from water-using unit i in plant A and B. $F_{m,aj}$ and $F_{m,bj}$ are the outflows from the water main to water-using unit j in plant A and B. $F_{m,ww}$ represents the excess flow from the water main that cannot be reused and is sent to wastewater treatment. The mass balance of the water main is:

$$\sum_i F_{i,m} \times C_{i,m} = \sum_i F_{i,m} \times C_{m,out} \tag{2}$$

Where $C_{i,m}$ is the concentration of flow from water-using unit i to the water main, $C_{m,out}$ is the outlet concentration of the water main. All concentrations are in ppm. The outlet concentration of the water main, modelled as a sequence of a mixer and a splitter, can be calculated based on the mass balance with Eq(3):

$$C_{m,out} = \frac{\sum_i F_{i,m} \times C_{i,m}}{\sum_i F_{i,m}} \tag{3}$$

3. Illustrative case study

A two-plant site is used as a case study in this study, and the data (in Table 1) is adapted from the study of Fadzil et al. (2018).

Table 1: Limiting data of Plant A and B for the case study (adapted from Fadzil et al. (2018))

Plant A				Plant B	
Sinks	Flowrate (t/h)	Concentration (ppm)	Sinks	Flowrate (t/h)	Concentration (ppm)
ASK1	50	20	BSK1	20	0
ASK2	100	50	BSK2	140	50
ASK3	80	100	BSK3	10	400
ASK4	70	200			
Sources			Sources		
ASR1	105	50	BSR1	120	100
ASR2	70	100	BSR2	50	800
ASR3	70	150			
ASR4	60	250			

A single water main is considered for the two-plant site, as more water mains would have less practicability due to the high increase of pipeline construction cost.

3.1 Freshwater targeting with Water Surplus Diagram (plant-level)

The Composite Curves of plant A and B are plotted on a concentration versus cumulative flow rate diagram based on the data in Table 1, as shown in Figure 2a and 2c. The freshwater flowrate is estimated using the Composite Curves so that the Source Curve is located on the right side of the Sink Curve. The areas between the Source and Sink Curves are then calculated and cumulated to plot the WSD (Figure 2b and 2d), with the contaminant concentration of all flows as the y-axis. Adjust the freshwater flow rate until the WSD locates exactly to the right side of the y-axis. In the plant A, the Pinch Point occurs at a concentration of 150 ppm, with a minimum freshwater flowrate of 43.3 t/h, with a wastewater flow (excess sources) of 48.3 t/h. Figures 3c and 3d presents the Water Sources and Sink Composite Curves and WSD of plant B. The Pinch concentration is 100 ppm, with minimum freshwater consumption of 90 t/h. Two excess source flows with a flowrate of 40 t/h at 100 ppm, and 50 t/h at 800 ppm are sent to wastewater. The Total Site without integration shows a freshwater requirement of 133.8 t/h and wastewater generation of 138.3 t/h.

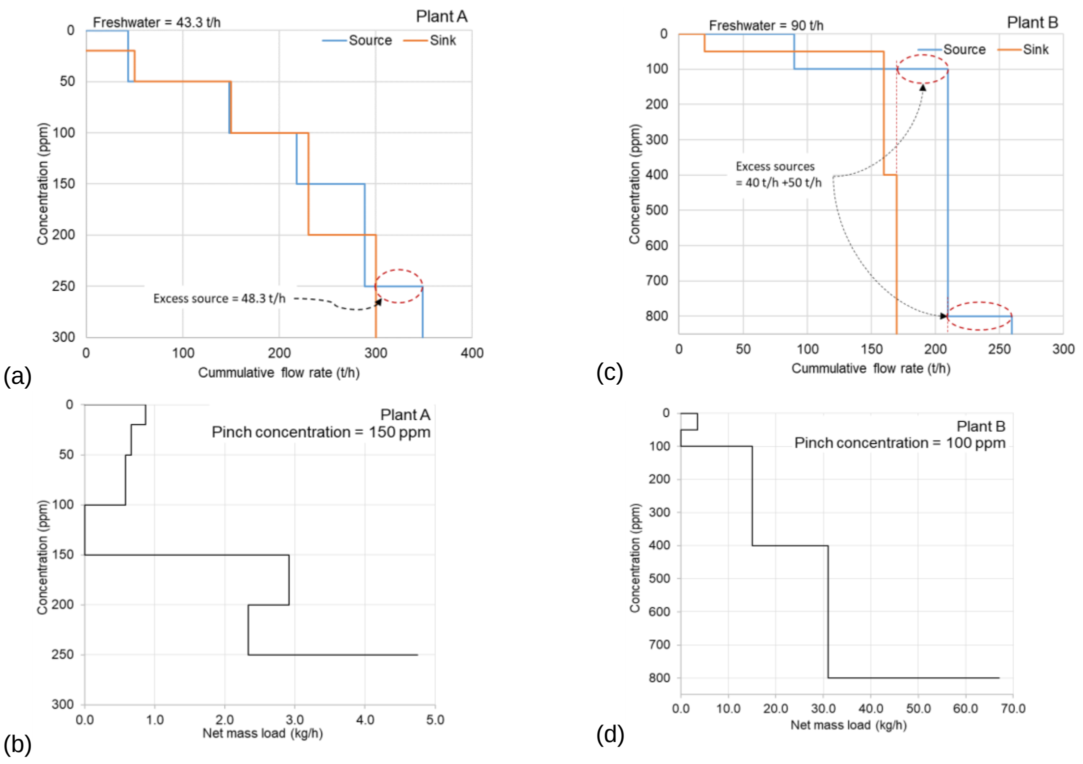

Figure 2: Water-Source and Water-Sink Composite Curves (a,c) and the WSD (b,d) of plant A and B

In Intra-Plant Water Integration, the excess flows of 48.3 t/h at 250 ppm, 40 t/h at 100 ppm in plant A, and 50 t/h at 800 ppm in plant B are sent to wastewater treatment, which might cause water sources waste. A water main can be installed to collect the excess sources flows for possible reuse in Total Site level. Instead of complex water networks in Total Site Water Integration, Water Integration with water mains could remarkably reduce the pipeline construction as it only connects the eligible sources and potential sinks.

3.2 Total Site Water Integration with water main

The excess sources after Intra-Plant Water Integration are sent to the site water main (Table 2). The selection of water main inlet concentration is important, as it decides the structure of the water reuse network. In this case, there are three excess sources with three concentrations of 100 ppm, 250 ppm, and 800 ppm, which become the candidates for water main inlet concentration.

Table 2: Eligible source flows for the water main

Sources	Flowrate (t/h)	Concentration (ppm)	No
Plant B	40	100	Excess Flow 1 (EF1)
Plant A	48.3	250	EF2
Plant B	50	800	EF3

Four scenarios are analysed, as shown in Table 3. Scenario 1 (S1) is without Total Site Integration. Scenario 2 (S2) is the Total Site Integration without water main. In this scenario, it can be assumed that the theoretical inlet concentration of the water main is 0 ppm, which does not allow any non-fresh sources to enter. Scenarios 3, 4, and 5 have water main inlet concentrations at 100 ppm, 250 ppm, and 800 ppm. The outlet concentration of the water main is calculated with Eq(3) and listed in Table 3. The excess flows are considered as additional sources to the two plants to determine the freshwater targets and wastewater generation using the WSD approach. The Composite Curves and WSD of S3 are introduced and discussed in detail. In S3, a water main with an inlet concentration of 100 ppm is installed in the site. As shown in Table 3, there is only one source flow at 100 ppm (EF1) sent to the main for further reuse, and sources with higher concentration are directly sent to wastewater treatment. This flow is taken as the excess source to plant A and B to determine the minimum freshwater input and wastewater generation.

Table 3: Scenario Descriptions

Scenario No.	Water Main Concentration (ppm) Inlet	Outlet	Water Main Flowrate (t/h)	Description
S1	/	/		Intra-Plant Water Integration
S2	0	0	0	Total Site – no water main
S3	100	100	40	After Intra-Plant Water Integration, Total Site – with water main
S4	250	182.1	88.3	
S5	800	405.4	138.3	

The Source and Sink Composite Curves of plant A with the additional source are constructed in Figure 3a.

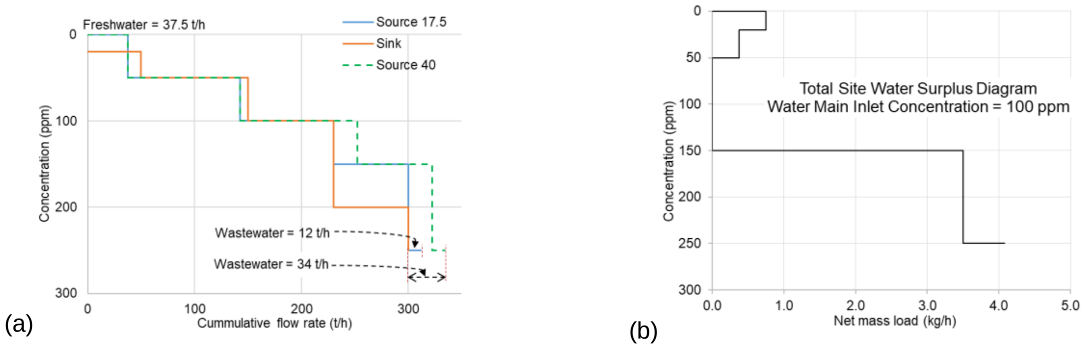

Figure 3: Water Source and Sink Composite Curve (a) and WSD (b) of S3 in plant A

The Water Source Composite Curve with the additional flow of 40 t/h at 100 ppm is shown with green dashes. The freshwater requirement decreased from 43.3 t/h to 37.5 t/h. It is also seen from the Composite Curves that the additional source (40 t/h, 100 ppm) is not fully utilised, but partially discharged as wastewater.

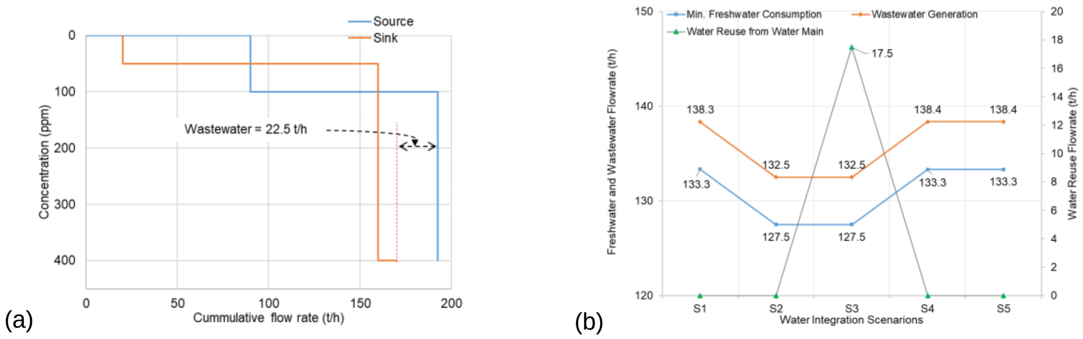

Figure 4a: Water Source and Sink Composite Curve with ES1 in plant B, b: Total Site minimum freshwater consumption, wastewater generation, and reuse in all scenarios

It is important to make sure all flows sent from the water main to the sinks are fully used to keep the piping efficiency. An effective flow of 17.5 t/h (100 ppm) is detected by the WSD resulting in the lowest wastewater discharge from plant A (12 t/h) with the lowest freshwater input.

The rest of EF1 is sent to plant B for further reuse, or to wastewater if it cannot be reused. In this case, as the sinks in plant B require cleaner water, EF1 cannot be reused in plant B. This is shown in Figure 4a where 22.5 t/h EF1 at 100 ppm is discharged as wastewater. Following the procedure, the minimum freshwater flowrate, wastewater generation and water reuse from the water main in all scenarios are summarised in Figure 4b.

When water main inlet concentration is 100 ppm, the site has the minimum values of the freshwater requirement (127.5 t/h) and wastewater discharge (132.5 t/h), and highest reuse (17.5 t/h). Water main inlet concentration at 0 ppm (S1) represents the Total Site without water main. It has the same freshwater and wastewater targets as S2. However, S1 features direct water reuse between the plant. The additional sources in water main are limited to further reuse because the sinks in the two plants have higher quality demands.

4. Conclusions

This study investigates the selection of Total Site water main concentration with a single contaminant. The proposed hierarchical procedure minimises the complexity of the water network of the site, leaving for Site-Level Integration only the excess supply and demand flows. The procedure evaluates the potential concentration levels for the water main, balancing the collection of water from the Site Water Sinks and delivery to the Site Water Sources. The case study illustrates the procedure and also evaluates the sensitivity of the resulting water utility demands for freshwater and water treatment towards the water main concentration level. The case study showed that a concentration of 100 ppm is selected as the optimal water main concentration, which reaches the lowest freshwater consumption of 127.5 t/h and wastewater of 132.5 t/h. The future work will explore the consideration of multiple water mains, water regeneration and capital cost.

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