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GUIDE TO INDUSTRIAL WATER CONSERVATION PART 1. WATER RE-USE IN SINGLE CONTAMINANT SYSTEMS

Associated software: AQUAINT

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GUIDE TO INDUSTRIAL WATER CONSERVATION PART 1. WATER RE-USE IN SINGLE CONTAMINANT SYSTEMS

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GUIDE TO INDUSTRIAL WATER CONSERVATION PART 1. WATER RE-USE IN SINGLE CONTAMINANT SYSTEMS

1. PURPOSE AND SCOPE

This Data Item forms part of ESDU's Guide to Industrial Water Conservation. It was developed under the guidance and with the contribution of a working party of experts drawn from industry. The membership list of this working party is listed on the inside front cover. Contact details for individual members is given in Appendix C.

Water conservation is an increasingly important requirement in the operation of process plant in a number of industrial sectors. These sectors include oil refining, chemical, fine chemicals, pulp and paper, food processing, textiles, dye stuff, pigments, metal processing and minerals extraction.

However, industrial water conservation (commonly referred to as 'water minimisation') is often poorly understood. The purpose of the Guide is to familiarise the engineer with the benefits of the application of water conservation technology, lead the engineer through necessary design tasks using working examples and provide tools (including computer software) to apply the methods.

One of the key practical methods of minimising the use of expensive, treated water (freshwater) is re-use of spent water. The task covered in this Data Item is ***the quick generation of the minimum required quantity of freshwater (the freshwater-use target) and the design of water re-use networks for single contaminant systems***. The methodology reported covers the current published state-of-the-art for single contaminant systems. ESDU are developing additional technology for more complex systems, such as multi-contaminant systems, which will be presented in later Data Items.

Truly single contaminant cases rarely occur. However, in many applications, pseudo-single contaminant properties such as suspended solids and total dissolved solids can be modelled as single contaminants. Guidance on problem definition and data collection is given in Section 6.

This Data Item describes a methodology for identifying the minimum amount of freshwater required by a system. This provides a means of identifying the maximum possible water savings that can be achieved by water re-use. The approach allows the identification of, within a system of multiple water-using operations, those operations which are critical for the achievement of a practical minimum use of freshwater (that is, the 'target' for freshwater use). This allows the engineer to focus data collection on those areas of the system.

A methodology for the identification of a water network structure which achieves the minimum water use target is also presented. However, whilst the key aim is water conservation, it is recognised that plant economics and operability are important factors which can control the implementation of any conservation scheme. Consequently, the Guide also examines ways in which such a structure can be modified in order to determine the most cost-effective design for a given system.

Water regeneration steps can also be incorporated into network design. Further, the suitable specification of a regeneration system can be identified as options are explored.

This Data Item is supplemented by a computer program, AQUAINT, which incorporates the procedures described in this Data Item. It allows rapid minimum freshwater-use targeting using the appropriate data and provides appropriate network design information. The use of AQUAINT is illustrated by a number of worked examples, including a full factory site (see Section 12).

2. NOTATION AND UNITS

		SI Units
C	concentration of contaminant in stream or system	ppm
C_{in}	contaminant concentration at inlet to operation	ppm
C_{out}	contaminant concentration at outlet from operation	ppm
C_{pinch}	concentration at pinch point on composite curve (see Section 7.1)	ppm
$\dot{L}$	mass flowrate of contaminant in a stream or operation (contaminant load)	kg/h
$\dot{M}$	mass flowrate of freshwater into system	t/h
$\dot{M}_{min}$	minimum mass flowrate of freshwater supplied into system (target freshwater-use supply, see Section 7.1)	t/h
x	refers to proportion of water regenerated (see Section 10.1.1)	
<i>Subscripts</i>		
$a, b, c, etc.$	refer to operations in system providing spent (used) water for re-use	
$avail$	refers to available spent (contaminated) water	
fw	refers to freshwater	
max	refers to maximum value	
$reqd$	refers to required value	

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3. ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

The implementation of water re-use is primarily driven by economic factors, which include the capital and unit cost of raw water supply, the cost of water disposal, environmental liability and the cost of non-compliance with discharge consents. The capital and operating costs associated with any water re-use technology should also be considered.

On occasions, savings made in terms of reductions in raw water use may be small. However reducing water volumes will affect costs of on-site pumping and site maintenance, water heating or cooling costs. Other benefits may include increased product recovery. Most significantly, a reduction in water use may have a very marked effect on the processing capacity of effluent treatment plants and can result in major capital cost savings when a factory expansion is being undertaken. As overall pressure on water resources increases, reducing water consumption will minimise the impact that water supply restrictions may have on plant output.

The costs of both effluent treatment and water regeneration processes are highly dependent upon the volume of water being treated. Optimising regeneration processes can result in significant cost savings.

Plant managers should have a strategic understanding of how water can be efficiently used. There are many reasons for this:

- (i) Regulatory regimes are moving towards tougher controls on abstraction of high quality water, and increased use of water from alternative lower quality sources is an important means of reducing this demand.
- (ii) Reduction in overall demand may increase the lifetime of the supply infrastructure.
- (iii) It is important that management accounts for issues of long term security of water supply. There are significant financial implications associated with step changes in water supply.

To safeguard against water problems impacting upon business a working knowledge of plant processes, associated water requirements and options for reducing water demand are required.

World wide government legislation is being put in place to protect the environment. The United Nations Earth Summit on Environment and Development (1992) resulted in governments of member nations agreeing to promote and enforce sustainable development, 'meeting the needs of the present without compromising the ability of future generations to meet their own needs'.

This trend is set to increase with the United Nations Environment Programme Global Environment Outlook Survey (GEO 2000)⁵ identifying quantity and quality of water resources as being one of the most cited issues of environmental concern. The survey also predicts that by the year 2025 two out of three people on earth will live in water stressed conditions.

Economic and legislative factors have resulted in a business environment where an increasing number of companies seek to implement environmental management systems, produce environmental reports and obtain certification in environmental standards such as ISO 14001.

4. MEANS OF CONSERVATION

On an industrial site water is used for both domestic-type and operational applications. In operational applications water is used in a number of ways including the following:

- **As a by-product or constituent of a reaction**

Water may be contained in raw materials within a reaction process, or as part of the product.

- **In contact with process materials in mass transfer**

Contaminants such as dirt or organic matter are often transferred to water in, for example, a washing operation. Alternatively during a process such as salt extraction, salts are transferred to water by aqueous extraction.

- **In general cleaning of equipment**

Examples include the cleaning of vessels, containers, floors, etc.

- **As a heat transfer fluid**

Water may be used to either heat or cool process streams in heat exchangers. For example, steam systems/boilers are commonly used to heat process fluids. Steam generation produces waste water in the form of blowdown and condensate loss.

Cooling water is frequently used to remove heat from a process. Some of this water is lost through evaporation in cooling towers and some cold reservoir water is sent to waste (blowdown) when it is necessary to control the levels of dissolved solids in the cooling water.

It is reported⁸ that nearly forty percent of water use in industry is accounted for by heat transfer processes.

- **As a process transport agent**

Water is often used as the medium to carry material through a process.

Whatever the application, there are three basic means of reducing water consumption, as follows:

- (1) Operational changes (see Section 4.1).
- (2) Water re-use (see Section 4.2).
- (3) Water regeneration (see Section 4.3).

4.1 Operational Changes

Operational changes can be used to reduce the demand for water. These changes are often the first instinctive measure taken to minimise water use, and often include:

- Using spray balls for more effective internal vessel washing.
- Changing from wet cooling towers to dry units or from the use of cooling water to air-cooled exchangers.
- Improving control of cooling tower blowdown, using for example automatic control based on monitored levels of solids.
- Fitting triggers to hoses to prevent unattended running.
- Improving energy efficiency to reduce steam demand and hence reduce the wastewater associated with the steam system.

Such improvements can be significant, but tend to be made on an ad-hoc basis with no consideration of the water-use requirements of the whole process or system.

When a targeted approach to water re-use is adopted these changes may take on a different perspective.

4.2 Water Re-use

Water re-use is achieved when the outlet water from one operation is used to satisfy the requirement of another operation. This is possible where the level of previous contamination does not interfere with the process. The strategy reduces both freshwater and wastewater volumes but leaves the contaminant load substantially unchanged.

Water re-use may be best achieved by blending spent water from one operation with freshwater and/or spent water from another operation, before being supplied to a subsequent operation.

Re-use of spent water from domestic operations is sometimes possible provided proper safeguards are implemented⁹.

4.3 Regeneration of Waste Water

A regenerative process is any operation that removes some or all of the contaminants⁶. Waste water can often be regenerated by partial treatment to remove contaminants and then re-used in other operations. Common examples include:

Biological treatment	Evaporation	Precipitation
Carbon adsorption	Filtration	Solidification and stabilisation
Centrifugal separation	Flotation	Solvent extraction
Chemical oxidation	Gravity separation	Stripping
Crystallisation	Ion exchange	Thermal treatment
Electrodialysis	Membrane separation	

It is sometimes helpful to differentiate between operations in which water is regenerated and returned to the same operation and those in which water is re-used only in other operations.

‘Regenerative re-use’ is taken to refer to the case where water does not re-enter processes in which it has already been used. Regenerative re-use reduces freshwater and effluent volumes. Again re-use after regeneration may require blending with spent water from other operations or with freshwater.

‘Regenerative recycle’ refers to the case in which regenerated water is returned to the original operation. Freshwater and effluent volumes are reduced and, again, effluent load is reduced by the use of a regeneration process.

Recycling can in some circumstances create a build-up with time of undesired contaminants that are not removed in the regeneration process. These contaminants might initially be present only in very low concentrations.

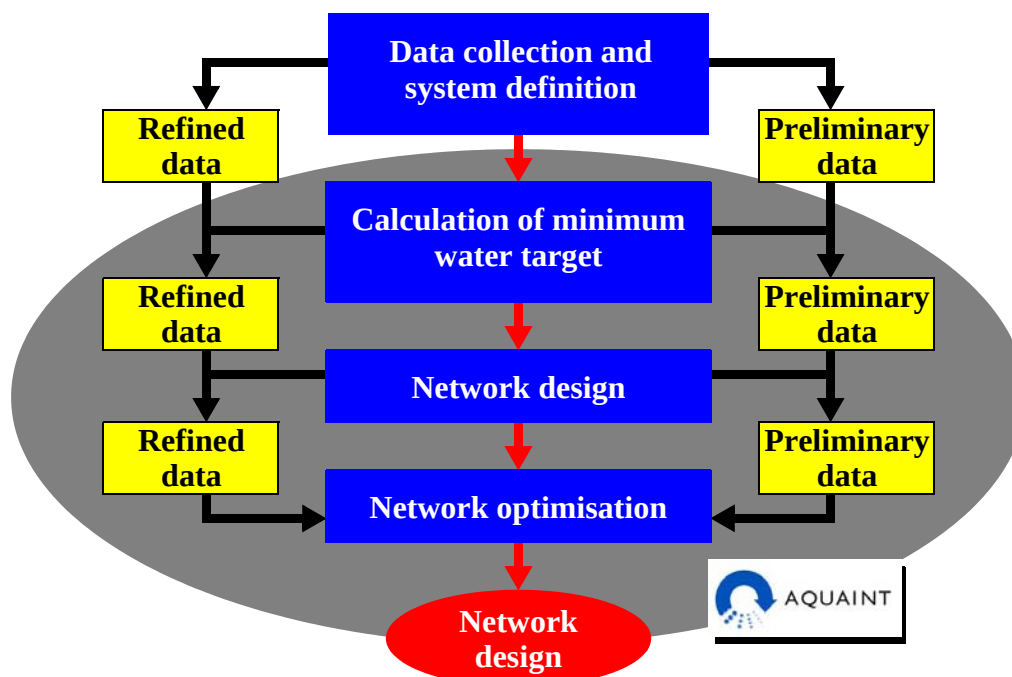
Further guidance on regeneration is given in Section [10](#).

5. STAGES IN ANALYSIS AND NETWORK DESIGN AND USE OF THIS DATA ITEM

The purpose of the methods outlined in this Guide and implemented within the computer program AQUAINT is to identify opportunities for water re-use in industrial systems. Water re-use reduces the amount used of clean, fresh water (referred to as freshwater) by re-using dirtier waste water.

The user is advised to follow the methods of this Data Item section by section, as the techniques build upon information given in previous sections.

There are four stages in the design of a water re-use network for a system of operations, as shown in Sketch 5.1.



Sketch 5.1 Stages in Network Design

5.1 Stage 1: Data Collection and System Definition

Because data collection can be costly, it is often best to collect data in stages. Initial data collection precedes system definition (see Section 6), and often it is possible to carry out the initial stages of network design before further data collection is carried out. The system may then be defined more accurately around newly-identified critical points that limit opportunities for water re-use.

The first objective of a data collection exercise is to derive a water balance, the accuracy of which should be set by the objectives of the particular study. Good practical guidelines for data collection and for developing a water balance are available from ETBPP². The first step to obtaining a water balance is to generate a schematic diagram of the water system. This can take the form of a simplified water distribution diagram with major sources and demands identified. The principal purpose of the schematic is to gain an outline *qualitative* understanding of the system. Readily available data can be noted and areas that are not well understood can be marked as such. More detailed *quantitative* data definition follows as and when appropriate. In a 'what if' study the accuracy may not necessarily need to be high. In fact, assessment of acceptable accuracy can form part of the 'what if' appraisal. In many instances some imbalance is acceptable but some level of data reconciliation is usually required.

The following are examples of some key features that should be noted in a 'what-if' study:

- Particular care must be taken regarding the identification and treatment of small (low volume) flows having high contamination levels.
- The arrangements used for handling rain water should be examined and the impact this has on site behaviour established.
- Streams that can be re-used should be identified and any constraints noted regarding stream mixing, etc.

When studying the process it may not be necessary to include all of the contaminants in various operations as part of the problem. When defining the system the objective is not to simulate the process but to represent the constraints that would prevent or allow the re-use of water. The analysis should be kept as simple as possible whilst including all critical elements to the problem.

One important type of 'what if' study is the examination of alternative freshwater sources or variation (such as seasonal changes) in freshwater quality on site needs.

The techniques within this Data Item can help identify critical specifications and allow assessment of how the stream data (that is, stream flowrates and their contaminant levels) affect both water consumption and network design. It is normally the case that the data set is incomplete, but it is important not to invest too much time in gathering stream data before initial analysis is carried out. The better the system is defined the more efficient the data gathering exercises will be. It is not necessary, and often not possible, to collect all data for all streams.

In switching between the use of freshwater and wastewater it is necessary to specify the maximum contaminant level that the operations can accept. In some cases this can be done 'scientifically' but in most cases these levels are 'best guesses'. Under these circumstances there may be a temptation on the part of the engineer to be very conservative in specifying these parameters, which can lead to missed opportunities for freshwater saving.

Details of all costs associated with water supply, use, treatment and disposal should be collected as part of the data collection exercise. The economic impact of operations and water use must be viewed at the same time as proposed changes are being considered.

Guidance on data collection and system definition is given in Section 6.

5.2 Stage 2: Calculation of Minimum Freshwater-use Target

The freshwater-use target is the minimum flowrate of freshwater required by the system, $\dot{M}_{min}$. The system may consist of an entire process plant or a network of water-using operations within the plant.

The calculation of the freshwater-use target allows the assessment of economic benefits accruing from the implementation of water re-use schemes. This calculation also generates a value for the 'pinch concentration', which is an important constraint in network design. The computer program AQUAINT calculates both the freshwater-use target and the pinch concentration.

Guidance on targeting for minimum freshwater use is given in Section 7 for quality-limited systems without regeneration or recycle and in Section 11 for mixed systems. For definition of these system types see Section 6 and the Glossary (Appendix B).

5.3 Stage 3: Network Design

Step-by-step procedures are presented to develop network designs that will achieve the minimum freshwater-use target. For complex systems that have a large number of operations, the procedures can involve the use of the “Remaining Problem Analysis” procedure within the computer program AQUAINT.

Methods for generating initial network designs that meets the minimum freshwater-use target are described in Section 9 for quality-limited systems and Section 11 for mixed systems.

Section 10 outlines the design procedure for including a water regeneration process within a re-use system.

5.4 Stage 4: Network Optimisation

Networks with minimum freshwater consumption may however not be the most economic solution. Often it is necessary to simplify the design, despite the cost of increased water consumption. Design refinement and simplification to obtain a more cost effective design with better operability is described in Section 13.

6. SYSTEM DEFINITION

Following an initial data collection, as described in Section 5.1, the engineer should be in a position to define the system. The key stages in system definition are as follows:

- (a) The forms of water contamination are identified.

The network design method described in this Data Item is suitable only for systems where the operation is limited by a single contaminant. Such limiting single contaminants include total solids, chloride ions, biological oxygen demand (BOD) or chemical oxygen demand (COD) or may be a specific contaminant (perhaps the concentration of a heavy metal such as cadmium) to meet a discharge consent.

- (b) Each operation within the system is classified into either of two generic types (see Section 6.1).
- (c) Water flowrate, the mass flowrate of the contaminant (referred to as 'contaminant load', expressed in kg of contaminant per hour) and concentration limits should be measured or estimated, as required, for modelling the various types of operations.

Data collection should focus on collecting enough information to give a basic picture of the process without focusing on unnecessary detail. Areas requiring the collection of further or more accurate data should be highlighted during the design procedure.

Re-use of spent water can require the mixing of spent water and/or freshwater streams. This should be undertaken with care. Before embarking on a study, practical constraints on mixing should be identified. For example, the water chemistry of any mixed streams should be studied to confirm acceptability.

6.1 Types of Operations

Classification of operations results in systems falling into one of three categories.

- (1) Systems consisting **solely** of **quality-limited** operations (see Section 6.1.1).
- (2) Systems consisting **solely** of **quantity-limited** operations (see Section 6.1.2).
- (3) **Mixed** systems consisting of **both** quality- and quantity-limited operations (see Section 6.1.3).

The procedures of this Data Item were developed for quality-limited and mixed systems. Techniques for a 'unified' procedure which covers all types of system will be the subject of a further Data Item.

6.1.1 Quality-limited systems

Quality-limited operations may be supplied with a varying amount of water dependant upon the concentration of the contaminant within the water.

Mass transfer operations frequently take the form of quality-limited operations. They are characterised by three properties:

- Contaminant load, $\dot{L}$ (expressed in kg/h)
- Maximum inlet contaminant concentration, C_{in} , for water entering the operation (ppm)

- Maximum outlet contaminant concentration, C_{out} , for water leaving the operation (ppm)

Contaminant load is the total amount of contaminant to be removed by the operation per hour.

The scope for re-using spent water from other operations is set by the maximum inlet and outlet contaminant concentrations for an operation, C_{in} and C_{out} , which are fixed by a number of possible considerations including:

- Minimum mass transfer driving force
- Maximum solubility
- A need to avoid precipitation of material from solution
- Fouling of equipment
- Corrosion limitations
- Product quality.

These considerations are often determined from operational experience. Some considerations can be quantified from values derived from laboratory tests, predictive tests or from published data. Others, such as exchanger fouling, are more difficult to quantify. When setting concentration limits the highest possible inlet concentration should be specified in order to maximise the opportunity for water re-use. These figures often have to be an estimate, however they can easily be revised when checking the final design.

Aspects of quality-limited systems are considered in Sections 7, 8 and 9.

6.1.2 Quantity-limited operations

Quantity-limited operations have a required flowrate of water. Water supplied to these operations may also be limited by a concentration constraint.

For network design purposes, quantity-limited systems consist of a series of water demands which may or may not have associated water returns/supplies of fixed flowrate.

Losses of water from the system (or water diversions) can be considered to be a form of water demand. Each water demand is characterised by a water flowrate and a maximum permissible contamination concentration.

Each supply is characterised by a fixed flowrate and a return concentration.

Examples of such operations are:

- Water being used for diluting caustic soda solution for subsequent consumption in a process. This would be characterised by a demand of fixed flowrate and concentration without providing any subsequent supply.
- Water being used in the wash part of a filtration cycle may be required at a fixed flowrate. This would be characterised by a demand of fixed flowrate and concentration. This water may however be available to be returned to the system (possibly at a high contaminant concentration). If water is being retained by the filter cake the subsequent supply would be a smaller quantity of water at a higher contaminant concentration.

Examples of the use of water demands and supplies in network design is given in Section [11.1](#).

6.1.3 Mixed quality-limited and quantity-limited systems

The methods used to optimise water re-use in mixed systems are described in n Section [11](#), and are based on those developed for quality-limited systems and the user is advised to read Sections [7](#), [8](#) and [9](#) before consulting Section [11](#).

7. QUALITY-LIMITED SYSTEMS WITHOUT REGENERATION OR RECYCLE

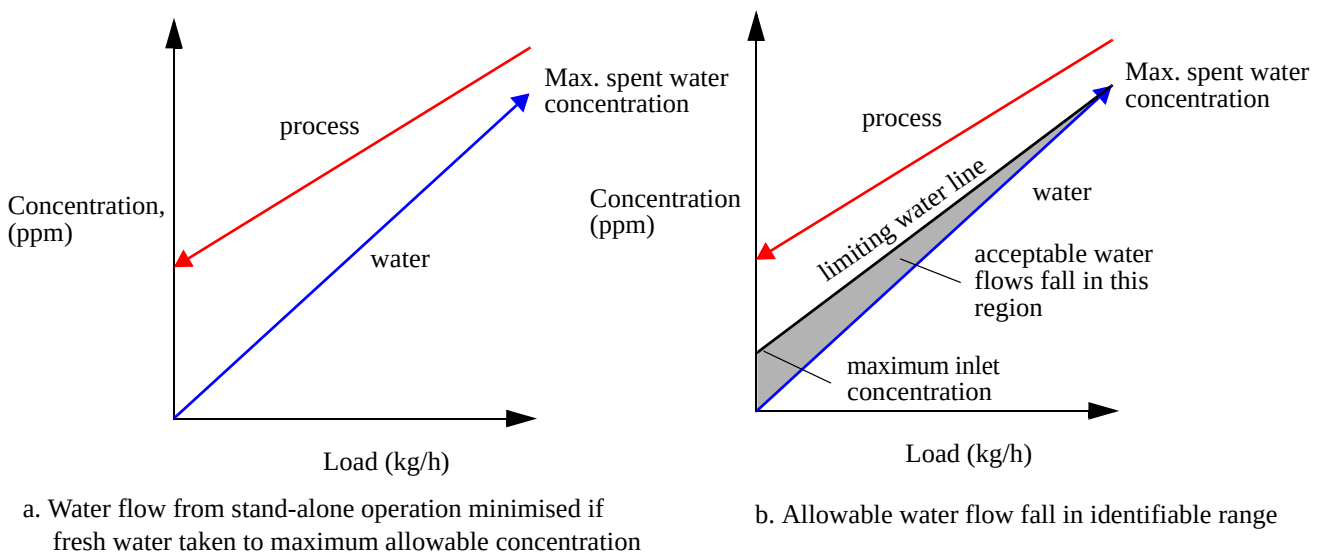
7.1 Targeting Procedure

Targeting procedures for quality-limited systems were developed by Wang and Smith^{3, 4}. Mass transfer operations (such as cleaning) that use water are represented on a plot of contamination concentration (C) against contamination load ($\dot{L}$), as shown in Sketch 7.1a. For efficient operation the concentration of the contaminant in the process stream must be higher than that in the water stream at all points.

The magnitude of the difference between process and water concentrations will be process dependent. It is characterised by the maximum inlet concentration, C_{in} (the highest concentration of contaminant acceptable for water entering the process) and maximum outlet concentration, C_{out} (the highest concentration of contaminant that is acceptable/achievable in water leaving the process). This specification may not be critical for all of the streams within a system. (The effect of individual specifications on subsequent water demand is established by the targeting procedure.)

For a quality-limited operation the quantity of water consumed in a single stand-alone operation is minimised if freshwater is used and taken to the maximum spent water concentration (Sketch 7.1a). The slope of this water line is equal to the inverse of the minimum freshwater flowrate. So, the steeper the water line the lower the freshwater flowrate.

The specified concentration limits define the 'limiting water line' for an operation (Sketch 7.1b). Any water profile positioned below this line (in the region shaded) would be acceptable for the quality-limited operation.



Sketch 7.1 Water lines

In a system with more than one operation requiring water the possibility of using spent water from one operation in a following (different) operation arises. Whilst the use of freshwater allows the minimum flow for a stand-alone operation, it is the limiting water line that defines the opportunities for using spent water from other operations. The potential for spent water re-use is maximised when the water used in the operation follows the limiting water line.

Most opportunities for water conservation by re-use are in systems with more than one operation, where it is necessary to look at the limiting water line, or profile, of the whole system. This profile is a "composite"

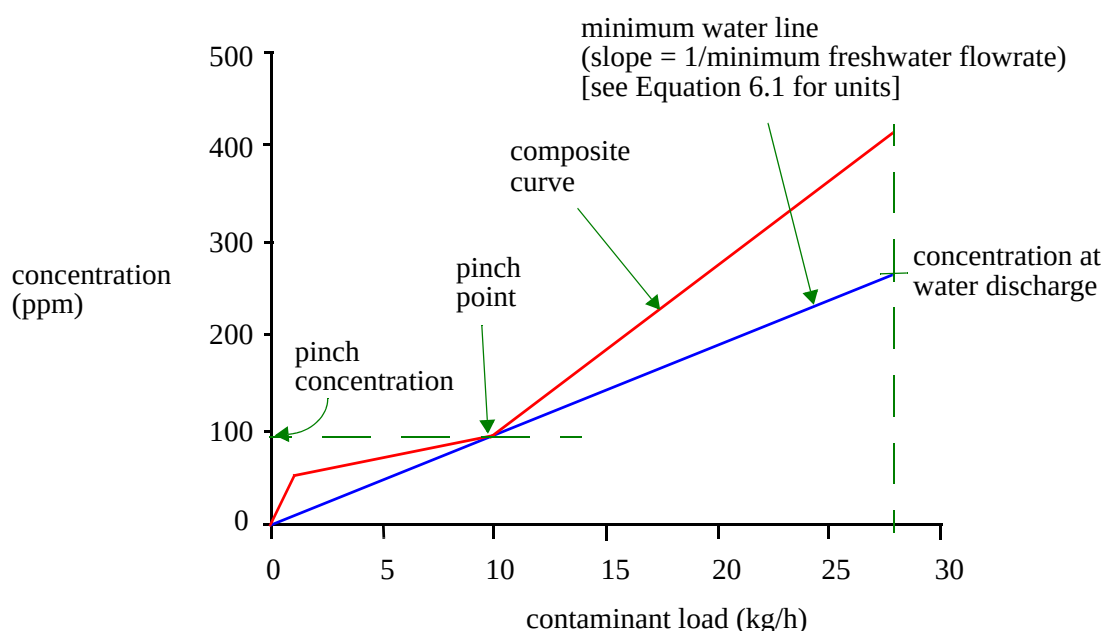
line, referred to as the **composite curve**, which is analogous to the heat demand composite curve used in thermal process integration integration (see ESDU 87030 and companion Data Items and software).

The composite curve, such as that constructed in Sketch 7.2, displays the constraints laid upon the design of the system. Again, any water line that falls below the composite is acceptable and the steeper the line the lower the freshwater flowrate. Thus, the minimum freshwater flowrate is calculated from the slope of the **minimum water line**, that is the line from zero load and specified freshwater inlet concentration (in this example 0 ppm) through the point of contact with the composite curve. (The minimum water line does not cross the composite curve.) The minimum freshwater flowrate, $\dot{M}_{min}$, is expressed in the convenient unit of tonnes per hour (t/h) in this Data Item and in the computer program AQUAINT, and is given by the equation

$$\dot{M}_{min} = \frac{\Delta \dot{L} \times 10^3}{\Delta C}, \quad (7.1)$$

where ΔC is the change in concentration, in ppm, over the change in contaminant load, $\Delta \dot{L}$, expressed in kg/h.

Each point where the supply line touches the composite curve creates a “**pinch**” in the design: there will be at least one pinch in a system.



Sketch 7.2 Composite curve and water line for system containing three operations]

The water line yields three important parameters:

- (1) the minimum water flowrate for the system, $\dot{M}_{min}$ (the inverse of the slope of the water line as given by Equation (7.1)),
- (2) the pinch concentration, C_{pinch} (that is, the concentration at the pinch point(s) where the water line and composite curve touch), and
- (3) the concentration of contaminants at the water discharge.

The minimum water flowrate for a system is important in network design and in the assessment of the total possible economic benefit from water conservation measures.

The pinch concentration is a focal point for the design process. The target minimum water consumption can be achieved in design by simply meeting two requirements:

- All water fed to the process must be taken to the pinch concentration.
- Water having a concentration below the pinch concentration must not be directly fed to an operation above the pinch concentration.

Below a pinch concentration point the process and water lines converge, and above that point they diverge: The diverging line indicates spare capacity to take up contaminant from other systems (see Section 12).

7.2 Worked Example

The application of the targeting procedure to a simple four stream operation illustrates how the targeting procedure is carried out. The system is defined in Table 7.1 in terms of maximum inlet and outlet concentrations and mass load of contaminant for each operation.

TABLE 7.1 Example data

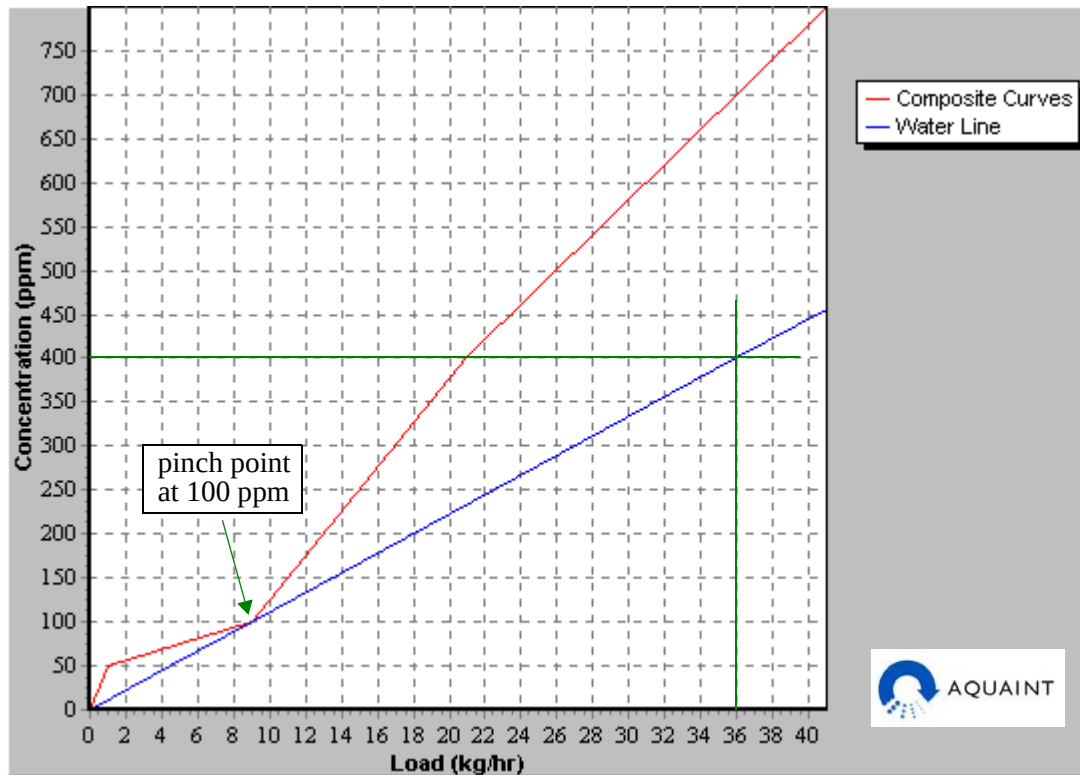
Operation No.	Contaminant load, $\dot{L}$ kg/h	C_{in} (ppm)	C_{out} (ppm)
1	2	0	100
2	5	50	100
3	30	50	800
4	4	400	800

The data are used to construct a composite curve for the system (Sketch 7.3) following these three steps:

- (1) identify concentration intervals,
- (2) determine operations occurring in relevant concentration intervals, and
- (3) calculate the load removed per concentration interval

Concentration intervals span each straight line region of the composite curve. Changes in slope of the composite curve occur when an operation is added to the system or when an operation is completed and therefore removed from the system. There are inlet and outlet concentration levels, C_{in} and C_{out} respectively, associated with the ends of each concentration interval (that is, the points of slope change). In the example in Table 7.1 these points are at concentrations of 0, 50, 100, 400 and 800 ppm: the concentration intervals are therefore at 0-50 ppm, 50-100 ppm, 100-400 ppm and 400-800 ppm.

When the intervals have been identified the streams that are present in each interval must be identified. The contaminant load removed in the interval is then calculated. Contaminant removal is assumed linear across the concentration interval so the amount of load removed in the interval can be easily calculated. For example, if an operation with $C_{in} = 0$ ppm and $C_{out} = 100$ ppm removes a contaminant load of 10 kg/h, then in the concentration span of 0-50 ppm a contaminant load of 5 kg/h is removed.



Sketch 7.3 Composite constraints curve and water line

The coordinates for this composite curve are given in Table 7.2 (note that load is represented cumulatively in order to represent the total contaminant load of the system). The value of contaminant load at any local value of concentration, C_i , is expressed algebraically as

$$\dot{L} = (C_i - C_{i-1}) \sum_{n=1}^n \frac{\dot{L}_n}{(C_{out} - C_{in})_n}, \quad (7.2)$$

where n is the number of operations. Only those operations with $C_{in} < C_i$ and $C_{out} \Rightarrow C_i$ are included in the calculation.