# Chapter 2
# Water Networks – Theory and Practice

**Peter Glavič and Miloš Bogataj**

**Abstract** In this chapter, an extended strategy for efficient and applicable water minimization in process industries is presented. The strategy effectively incorporates environmental, organizational and economic aspects accompanying the water minimization issue. The strategy was tested and applied in several water minimization projects involving chemical and process industries. Four case studies are presented for illustration purpose. The results obtained indicate that in most cases water efficiency can be greatly improved by using technologically, environmentally and economically viable solutions.

## 2.1 Introduction

Covering over 70% of the Earth's surface, water is unquestionably the most precious natural resource that exists on our planet, as it is essential for everything that grows and prospers on our planet. Although recognizing this fact, we are slowly but persistently headed towards water scarcity/unavailability on a global level. There are several factors, which contribute to lowering the water availability, but we point out two of them, which in combination accelerate the dynamics of fresh water reduction.

P. Glavič (✉) • M. Bogataj
Department of Chemistry and Chemical Engineering, University of Maribor, Smetanova 17, Maribor SI-2000, Slovenia
e-mail: peter.glavic@uni-mb.si
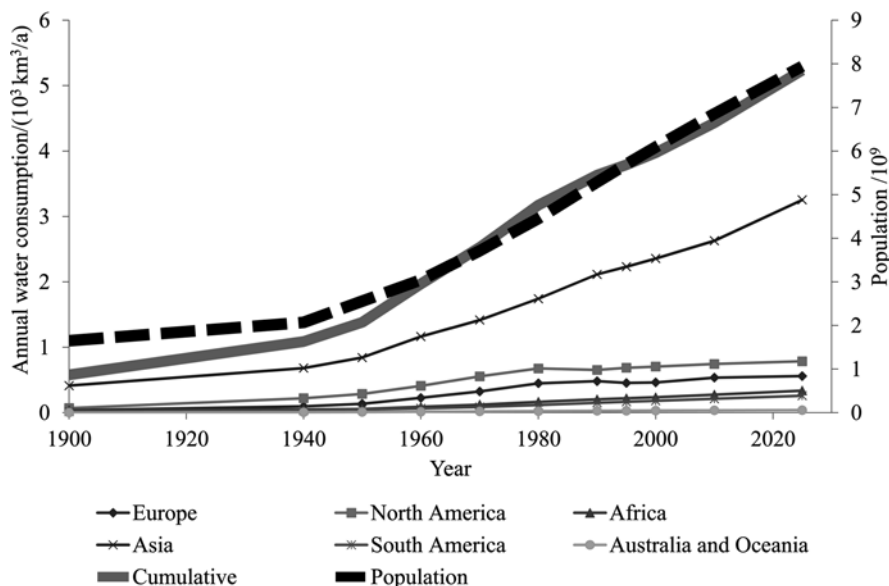
**Fig. 2.1** Water consumption and population growths (Source: UNESCO [17]; US Census Bureau [18])

The first one is that we are dealing with constant volume of usable Earth's water; however, its consumption is constantly increasing (Fig. 2.1) mainly due to population growth. Taking into account the prognosis of Earth's population reaching some 9.3 billion by 2050 [18] the water availability per capita is expected to drop severely.

The second is the industrial pollution. Water is an important resource for industrial activity. For example, water is used extensively in petrochemical plants, refineries, in food, textile and pharmaceutical industry. It is needed for various purposes, e.g. product formulation, washing, cooling, high-purity water makeup systems, general plant service water, waste conveyance/transfer, potable/sanitary service, and fire protection.

After being used in these processes, the water is commonly polluted with various contaminants, making it unsuitable for release into the environment without an efficient and often expensive treatment.

It is estimated that approximately 22% of water resources are being consumed by the industry (Fig. 2.2a). Currently, approximately 59% of these are being utilized by the industry in high-income countries (Fig. 2.2b). In contrast, industrial water use contributes 10% to the total water use in low-to-middle income countries (Fig. 2.2c). These numbers will rise with industrial production. It is expected that industrial water consumption will increase from estimated 870 $(km)^3 a^{-1}$ in the year 2010 to 1,170 $(km)^3 a^{-1}$ in the year 2025, which equates to 25% increase over the period of just 15 a (years) [17].

These trends clearly indicate that in order to provide sufficient volume of quality water for the future generations, efficient actions focusing on minimizing the industrial water consumption and pollution need to be taken now.
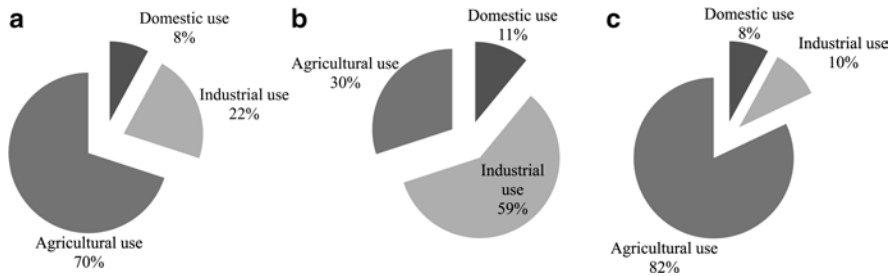
**Fig. 2.2** Competing water users (**a**) World (**b**) High-income countries (**c**) Low- and middle-income countries (Source: UNESCO [16])

## 2.2 Why and How to Reduce Water Consumption?

Water scarcity and economic consideration are perhaps the most obvious reasons or in other words, the most powerful driving forces to push the profit-oriented process industry into considering and implementing the steps towards reducing the water consumption. However, there are also other reasons, such as wastewater discharge permit compliance, priority of legislation banning, "good neighbour" policy, etc. which certainly motivate the water-using industries towards improving their water efficiency.

At the beginning of the second decade of the twenty-first century, several methodologies for minimizing water consumption in process industries are readily available. Reduction in water usage can be achieved by implementing the solutions obtained by either one or a combination of the following methods:

- Good water management practice
- Heuristic rules
- Various techniques based on systematic approaches:
    - Conceptual design methodology based on Pinch Analysis, commonly considered as the Water Pinch methodology and/or
    - Mathematical programming.

## 2.2.1 Good Water Management Practice

Good water management practice is based on collecting process data by constant monitoring. Water flow rate (especially the inlet and discharge streams) should be constantly measured, thus providing the data for water mass balances. In addition, the quality of water streams should be monitored in order to assess the contamination of water. It is only through the comprehensive monitoring that the real *status-quo* regarding the water consumption can be evaluated. In addition, by carefully analyzing

the mass balances, process failures, such as water leakages, spill-overs, underground water irruptions, etc. can be easily identified and prevented. Nonetheless, for achieving step-change improvements in water efficiency of a given process it is often needed to tackle the "water problem" with more elaborate methods.

### 2.2.2 Heuristic Rules

Heuristic rules are commonly obtained through experiences, testing and analysis of process data. These rules are valuable for *ad hoc* collection of potentially promising solutions and are often utilized in practical applications. An example of such a rule is to use a multistage (preferably counter-current) washing operation instead of a single stage one. Multistage washing operation utilizes the concept of water reuse, thus reducing the fresh water consumption, i.e. low quality water can be used in the initial stages, while high quality water can be used in the final stages. This rule can be generalized to: use water of the lowest allowable quality for any given operation. Other examples are replacing water cooling with air cooling, using lightly contaminated water to partially reduce fresh makeup water flow rate, improving control of boiler and cooling tower blow down, etc. [12].

### 2.2.3 Systematic Methodologies for Water Minimization

The water pinch methodology [9, 19, 20] is a graphical technique for reducing water consumption and wastewater generation through integration of water-using activities, or processes. It originates from mass exchanger network (MEN) synthesis method [4], which is analogous to that proposed by Linnhoff and co-workers for the design of heat exchanger networks [10, 11]. Similar to the latter it provides targets (minimum water consumption) ahead of the actual water network design. Once the targets are obtained, the water network is designed by a matching procedure.

The water pinch methodology is straightforward, simple and intuitive. Besides, it offers good insights into the problem itself as long as the problem is simple, i.e. water streams contain one contaminant at most. While sometimes there truly exists a water network with a single contaminant, or multiple contaminants can be lumped under certain circumstances into a single pseudo-contaminant, this is rarely the general case. When the assumption of a single contaminant does not apply, the water pinch methodology turns out to be somewhat cumbrous and impractical.

To avoid the above limitations we resort to approaches based on mathematical programming. The first systematic approach reported for water management problem was addressed as a water/wastewater allocation problem and formulated as a nonlinear optimization problem [13]. It took more than 10 years for the scientific/ engineering community to recognize the potential and implications of this work. However, in the past two decades several methodologies and approaches based on mathematical programming, addressing various water minimization problems in
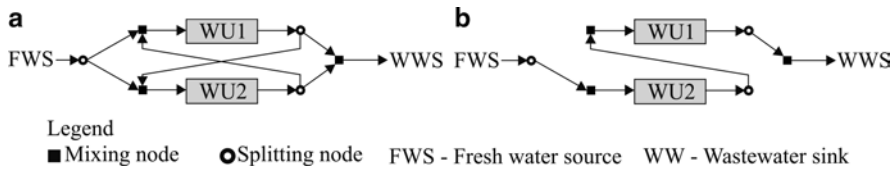
**Fig. 2.3** Water network superstructure (**a**) Simple two-water-using unit superstructure (**b**) Potential solution, embedded in the superstructure

numerous ways were developed. For a comprehensive review and discussion on the pros and cons of these approaches, the reader is referred to Bagajewicz [1], Dunn and El-Halwagi [3], Foo [5] and Jeżowski [6]. Nonetheless, we present and outline some basic features.

Common to these approaches is a superstructural representation of the water network (Fig. 2.3). In the simplest case, water from a single fresh water source (FWS) is fed to each water-using unit (WU). These are interconnected with streams via mixing and splitting nodes. In addition, each water-using unit is connected to a wastewater sink (WWS). The superstructure of a given problem is than coded into a mathematical program.

Depending on how the water minimization problem is postulated, the mathematical program takes a form of:

(a) *Linear program*, e.g. single-contaminant network, simple linear models of water-using units
(b) *Nonlinear program*, e.g. multi-contaminant network, detailed nonlinear models of water-using units
(c) *Mixed-integer linear program*, in general the same as (a), but with a possibility of handling continuous (e.g. water flow rates) and discrete decisions (e.g. cost, associated with existing connections) simultaneously
(d) *Mixed-integer nonlinear program*, the most general approach, it can handle all of the above.

The major advantage of the approaches based on the mathematical programming is that the objectives such as water consumption, water cost, wastewater treatment cost, and capital investment can be taken into account simultaneously. It was proven that the solutions obtained using these approaches were often superior to the ones obtained by heuristic rules or the conceptual approach. However, a profound knowledge of advanced mathematics, modeling and computer programming is usually a necessity.

### 2.2.4   Beyond Water Minimization

In the previous section, we presented the approaches for water minimization. However, in many cases the picture is broader than the water minimization alone. Besides water, energy is among the most important utilities used in the process
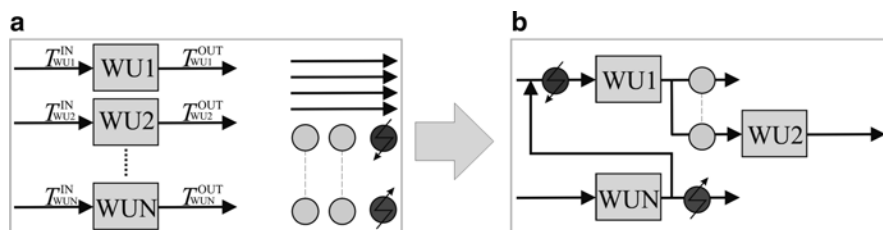
**Fig. 2.4** Task of designing a heat-integrated water network

industries. Moreover, in certain situations significant volumes of water need to be heated up or cooled down to meet process operating conditions. Consequently, high energy consumption in the form of cooling and heating utilities is needed. In such cases, when both the quality and temperature of water are important, water and energy management need to be considered simultaneously. Surprisingly, despite all the enabling technologies simultaneous consideration of water allocation planning for generalized, multi-contaminant water networks and heat integration has been scarcely addressed.

The problem of heat-integrated water networks can be stated as follows (Fig. 2.4). Given is a set of water using processes, which require water of adequate quality (contaminant concentrations) and temperature. The inlet and outlet temperatures generally are different for each process using water. Also, given is a set of heat exchangers, coolers, heaters and a set of process streams (Fig. 2.4a). The task is to determine the optimal network of water stream interconnections among the processes and the corresponding heat exchanger network (Fig. 2.4b) by simultaneously optimizing annual operating costs (fresh water, regeneration, and utility costs), and depreciation (of e.g. heat exchangers).

Bogataj and Bagajewicz [2] presented the approach based on mathematical programming. The problem was formulated as a mixed-integer nonlinear program on a basis of a superstructure, which comprises a water network, and a heat exchanger network superstructure. The key concept of their approach is that the target temperatures of water streams can be achieved either by direct heat transfer (mixing of streams) or by indirect heat transfer (heat exchangers) or both. Their method can be used in synthesis of single- and multi-contaminant heat integrated water networks. The designs are obtained in a single step, and show fairly low topological complexity. The latter is highly desirable for industrial application.

With the methods presented, economic and environmental aspects of the sustainable development can be addressed in a sufficient way. By using the above approaches, we tend to produce solutions with minimal negative impacts on the environment and solutions, which are at the same time economically efficient. However, to comply fully with the sustainable development paradigm, the next milestone in the development of water minimization approaches should be the inclusion of the third – societal aspect (e.g. process safety, health hazards). The latter can be achieved by using indicators of sustainable development [7, 8].

### 2.2.5   Water Minimization Strategy

Evidently, many approaches can be used to tackle the water minimization problem, and there are many ways to address it. Each of the approaches has arguments in favor or against using them. Overall, water minimization is a challenging task, especially because criteria like technical ability, reliability, control, uncertainty, impact on process/product quality, secondary waste generation have to be considered in the final design. Based on our experiences we propose the strategy shown in Fig. 2.5.

After the need for water minimization is recognized, goals and working schedule are set. In addition, for the project to be successful a support from company's management team is vital even at this early stage.

Next, the assessment stage follows. It is crucial to obtain the most current, accurate, and overall representative data (i.e. water/wastewater quality, process demands, flow rates, etc.). The data are needed for calculating the water balances and for the subsequent design stage.

In the design stage, alternative solutions of the problem are generated. For this purpose, either an approach based on heuristics, or a systematic approach can be used. Preferably, the approaches should complement each other. After the alternatives (preliminary designs) are obtained, detailed technical and economical evaluations, as well as evaluations considering reliability, control, uncertainty, etc., are carried out.

Finally, the most promising alternative is selected and implemented.

## 2.3   Case Studies

Four case studies are presented in this section, all based on real, large-scale industrial processes. The approach used in all the case studies follows the flowchart given in Fig. 2.5 (see Sect. 2.2.5).

### 2.3.1   Textile Dyeing Mill

Textile industry is one of the largest water pollutants. Among various process operations common to textile industry, the dyeing processes and accompanying washing/rinsing operations are especially problematic, as vast volumes of water are utilized, mainly in a function of a solvent. What alarms the most is that the water needs to be of relatively high quality as it enters the dyeing mill, but is generally heavily loaded with organic and inorganic pollutants as it is being discharged to an on-site or municipal wastewater treatment facility. In this case study, various opportunities are proposed for reducing the water consumption in a textile dyeing mill.
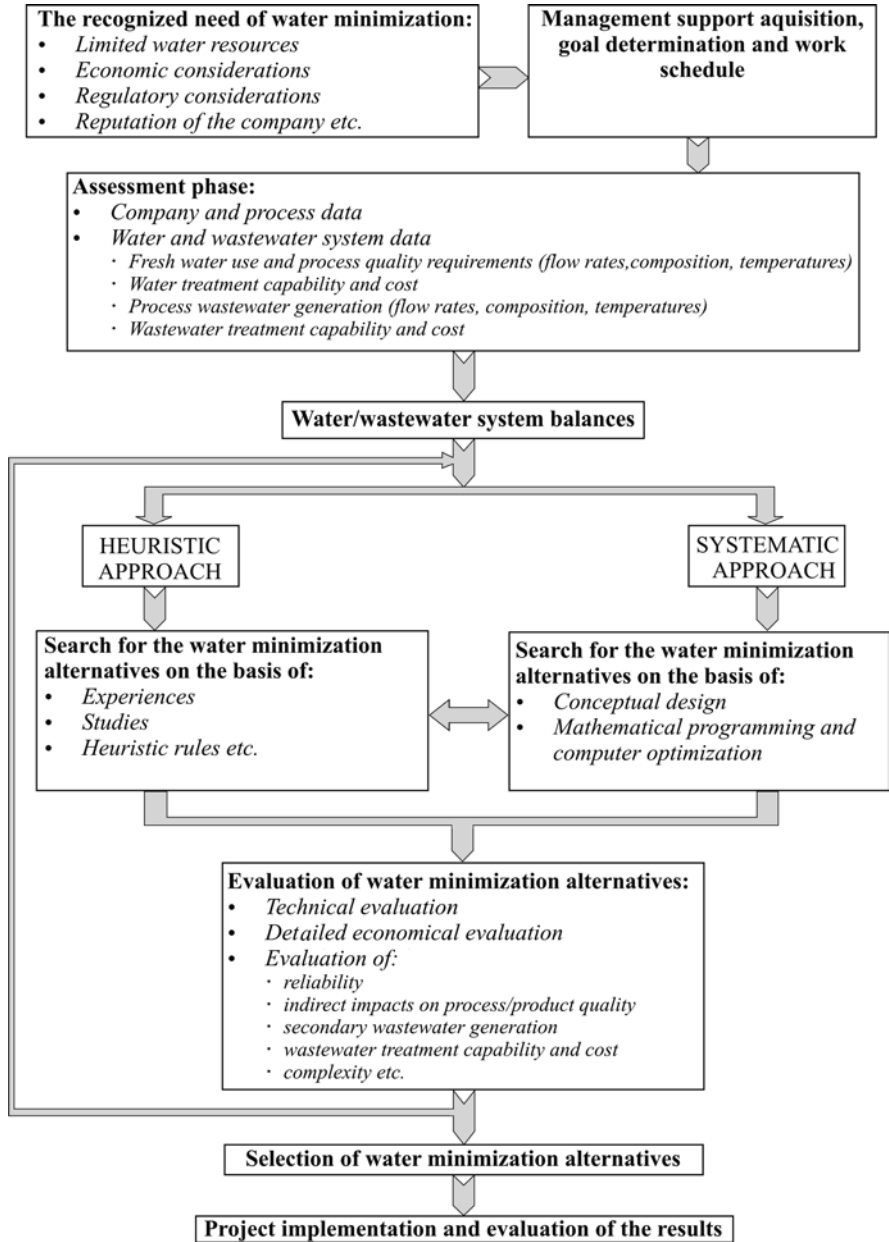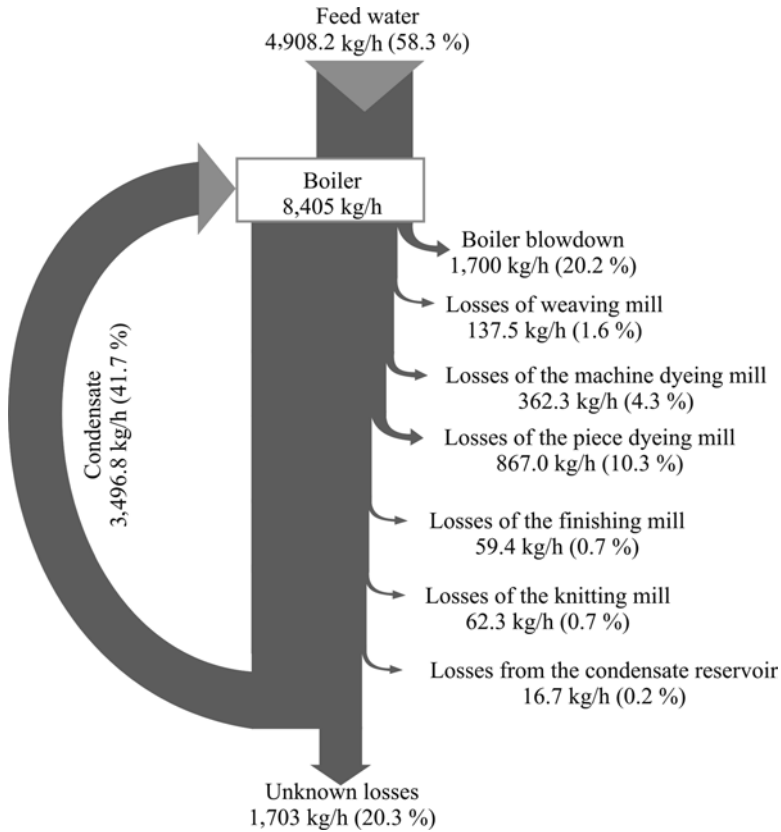
**The recognized need of water minimization:**
- *Limited water resources*
- *Economic considerations*
- *Regulatory considerations*
- *Reputation of the company etc.*

**Management support aquisition, goal determination and work schedule**

**Assessment phase:**
- *Company and process data*
- *Water and wastewater system data*
  - *Fresh water use and process quality requirements (flow rates, composition, temperatures)*
  - *Water treatment capability and cost*
  - *Process wastewater generation (flow rates, composition, temperatures)*
  - *Wastewater treatment capability and cost*

**Water/wastewater system balances**

HEURISTIC APPROACH

SYSTEMATIC APPROACH

**Search for the water minimization alternatives on the basis of:**
- *Experiences*
- *Studies*
- *Heuristic rules etc.*

**Search for the water minimization alternatives on the basis of:**
- *Conceptual design*
- *Mathematical programming and computer optimization*

**Evaluation of water minimization alternatives:**
- *Technical evaluation*
- *Detailed economical evaluation*
- *Evaluation of:*
  - *reliability*
  - *indirect impacts on process/product quality*
  - *secondary wastewater generation*
  - *wastewater treatment capability and cost*
  - *complexity etc.*

**Selection of water minimization alternatives**

**Project implementation and evaluation of the results**

**Fig. 2.5** Flowchart of water minimization strategy

**Fig. 2.6** Material flow rates of steam losses and condensate return in textile dyeing mill presented in the form of a Sankey diagram

### 2.3.1.1    Water Minimization Options Proposed

For keeping the water consumption of any given water using process as low as possible – be it state of the art or somewhat out-dated technology – good house-keeping and regular maintenance are of crucial importance. Based on detailed analysis of the water flow rates and the existing process equipment in the textile dyeing mill, the following improvements were proposed [23]:

- After-washing in machine dyeing mill can be shortened, and pre-washing in piece dyeing mill can be banned without a negative impact on the quality of the product
- New dye kitchen installation
- Cooling water can be reused for dyeing and rinsing
- Condensate can be reused as a boiler feed water (Fig. 2.6)
- Boiler blow down can be reused for heating of buildings
- Steam losses can be reduced by substituting steam traps with more efficient ones.

#### 2.3.1.2   Economical and Environmental Benefits

Implementation of the proposed solutions could cause 21% reduction in wastewater flow rate produced (153,000 m$^3$ a$^{-1}$), and 15% reduction in soft water demand (78,300 m$^3$ a$^{-1}$). Furthermore, substantial savings in dyes consumption (7,300 t a$^{-1}$) and consumption of other chemicals (73,800 t a$^{-1}$) were proposed. Steam demand can be decreased by 25% (8,100 t a$^{-1}$), causing the 15% (342,000 m$^3$ a$^{-1}$) decrease in consumption of natural gas utilized as a fuel in the boiler house. Investment was estimated to 67,000 €. With annual savings of 237,600 € a$^{-1}$, the payback time was approximately 0.25 a.

### 2.3.2   Refinery and Petrochemical Complex

The petrochemical complex comprises formaldehyde, methanol and synthetic resin production processes. Formaldehyde is produced in two lines that differ in capacity. Some of the wastewater produced in the two lines is reused; however, 2.3 m$^3$ h$^{-1}$ (hour) of wastewater still ends in the sewer. Methanol is produced by a catalytic conversion of synthesis gas in a Lurgi low-pressure process, consisting of three main steps:

- Production of synthesis gas
- Catalytic conversion of methanol
- Processing of crude methanol.

In the methanol production process, cooling water is being used for cooling samples and condensate. In total 6.5 m$^3$ h$^{-1}$ of cooling water is needed, which after being used, ends as a wastewater. Urea-formaldehyde and phenol-formaldehyde synthetic resins are produced in two synthetic resin plants. Their operation requires 16.9 m$^3$ h$^{-1}$ of surface water for vacuum pumps. In addition to this, other users consume 2.3 m$^3$ h$^{-1}$ of potable and cooling water. The refinery comprises three atmospheric distillation columns for oil refinement. Out of 9.2 m$^3$ h$^{-1}$ of wastewater produced, 2.2 m$^3$ h$^{-1}$ of that is unpolluted wastewater.

In total, the refinery and petrochemical complex produce 37.2 m$^3$ h$^{-1}$, or roughly 268,000 t a$^{-1}$ of wastewater.

#### 2.3.2.1   Water Minimization Options Proposed

On the basis of technological wastewater analysis and after the characteristics of the individual water streams were established, new interconnections of water outflows from the processes or process units, and potential water consuming processes were identified [21].

The first proposal addresses the concept of wastewater regeneration reuse. Acidic wastewater from the storage tank of the formaldehyde production process can be
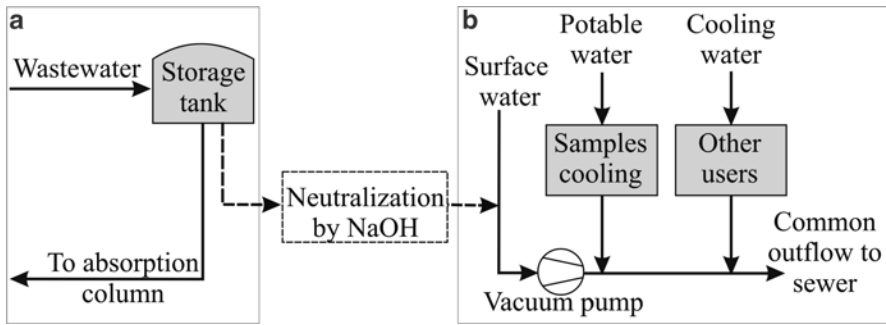
**Fig. 2.7** Possible wastewater regeneration reuse (Adapted from [21]) (**a**) Formaldehyde production process (**b**) Synthetic resin production process
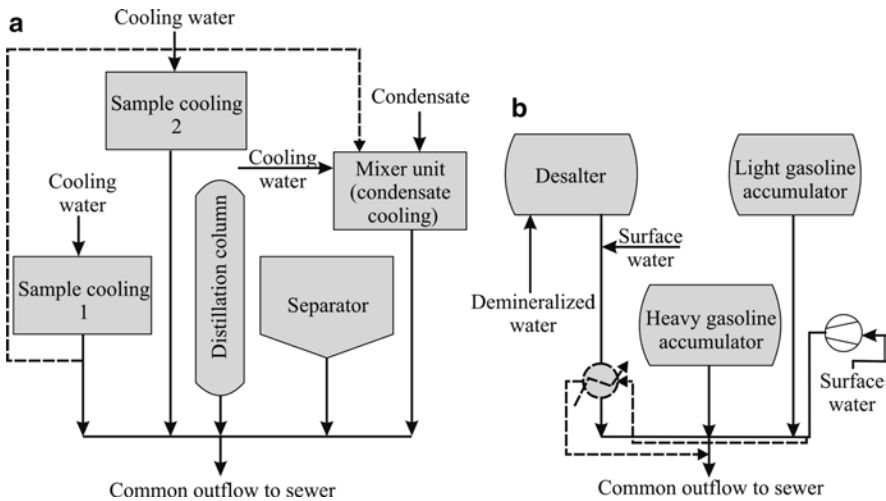


**Fig. 2.8** Water-flow diagram including the proposed improvements (Adapted from [21]) (**a**) Methanol production process (**b**) Atmospheric distillation

regenerated (neutralized by alkali) and then reused in the synthetic resin production process to reduce the surface water intake for the vacuum pumps up to 60% (Fig. 2.7).

A direct water reuse within a process was found to be a feasible option in the case of the methanol production process. A fraction of cooling water used from sample 1 cooling stage can be reused for direct cooling of condensate by mixing of streams. The solution is graphically represented in Fig. 2.8a.

The third proposal refers to the refinery and deals with the reduction of water needed for cooling the desalter outlet stream (Fig. 2.8b). It was feasible to use pump outlets for desalter outflow cooling.
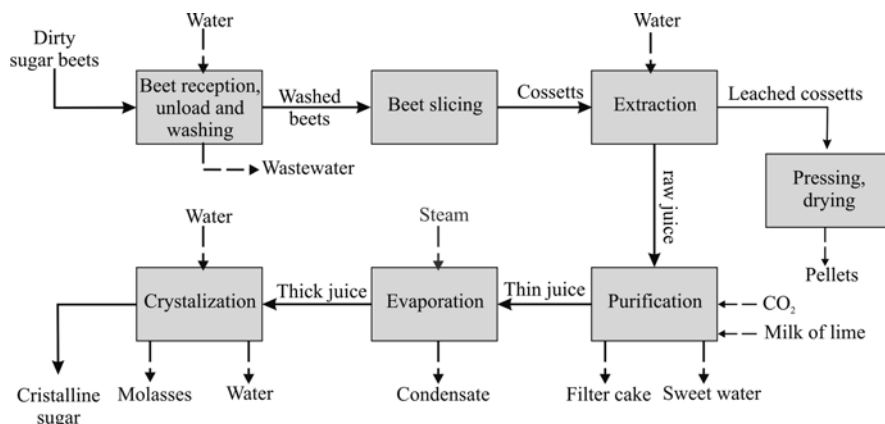
Fig. 2.9 Process flow sheet of a sugar beet extraction process (Adapted from [22])

#### 2.3.2.2   Economical and Environmental Benefits

The three proposals could result in total savings of 43,100 € a$^{-1}$, 24% reduction in total volume of water used in the petrochemical process, and 14% reduction of the total volume of water used in the refinery. The payback time for the investments into the improvements of petrochemical complex was estimated to 0.5 a. As for the refinery, the payback time was estimated to 11 days only. It should be mentioned that 1 year after this study was performed; the increased water tax would double the above reported savings.

### 2.3.3   Sugar Beet Extraction Plant

The objective of sugar beet processing is to extract pure sugar from the beet while separating pulp and non-sugars such as minerals and water. A typical sugar beet contains (in mass fractions): 76.0% water, 17.0% sugar, 3.0% soluble non-sugar materials, and 4% fibres. Beside the main product, sugar, two valuable by-products, molasses and pulp proceed from the sugar beet processing. Processing 4,200 t day$^{-1}$ of sugar beets requires 2,000 t day$^{-1}$ of fresh water and produces roughly 4,600 t day$^{-1}$ of wastewater. The latter is in part a consequence of high water content in sugar beet.

A simplified process flow sheet of sugar manufacturing process is given in Fig. 2.9. The main stages are:

- Beet reception, unloading, washing and storing/transporting
- Beet slicing and cossettes (cut up beets) extraction, leached cossettes drying and pelleting
- Raw sugar purification (liming, carbonation, filtration)
- Thin juice evaporation
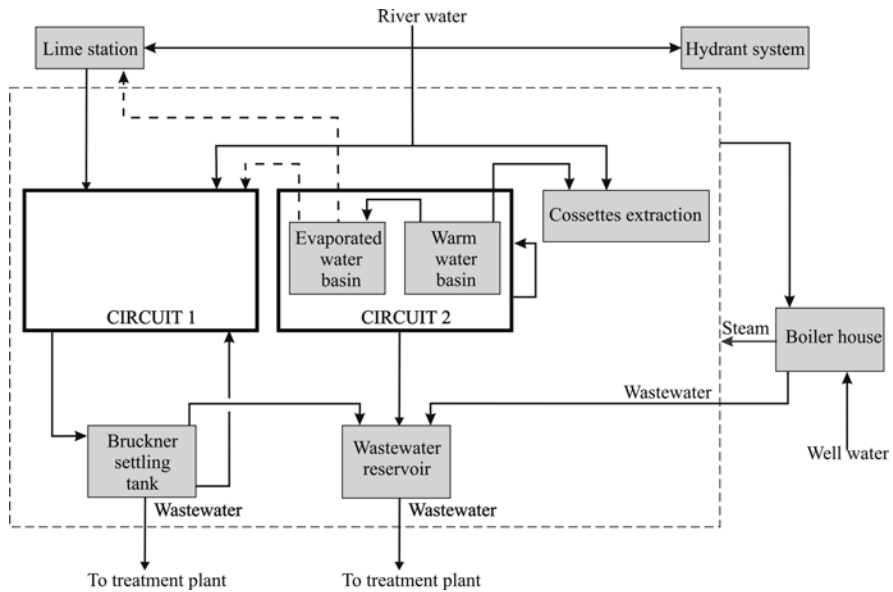- Thick juice crystallization (boiling and centrifugation).

**Fig. 2.10**  Fresh water/wastewater flow sheet in a sugar beet extraction process (Adapted from [22])

There are several water and wastewater streams used or generated in various operations of the sugar plant. The streams have specific characteristics and require different handling or treatment. In the sugar plant studied, there are four qualitatively dissimilar water streams and circuits, respectively (schematically shown in Fig. 2.10):

- Fresh water (well water, river water)
- Wastewater
- Water recycle used for unloading, transporting, and washing of beet (circuit I)
- Condensate, warm water, cooling water, and evaporated water recycles from the crystallization stage (circuit II).

### 2.3.3.1  Water Minimization Options Proposed

After a detailed survey of water and wastewater streams was carried out, several options for water minimization were established using a heuristic approach and considering the selection criteria like costs, technical ability, reliability, complexity, impact on process/product quality, secondary waste generation, etc.:

- Water in the evaporated water basin can be disinfected, and reused partially in the lime station and partially in circuit 1 (dashed lines in Fig. 2.10);
- Condensate from the evaporation stage can be recovered and used as a feed water for the boiler;

- Irruptive water flow into the flume system must be limited, thereby reducing the expenses for water tax;
- River water intake can be reduced by replacing a part of it with water from the warm water basin.

#### 2.3.3.2 Economical and Environmental Benefits

Assuming that all the proposed improvements are implemented, the fresh water intake is to be reduced by 69% (216,000 $m^3$ $a^{-1}$). Total savings per season are estimated to 42,500 €. Payback time for the required investment is planned to be approximately 5 d.

### 2.3.4 Brewery

The brewery considered in this case study has a production capacity of approximately 1,000,000 hL $a^{-1}$. The volume ratio of water consumed to beer sold is 6.04 L $L^{-1}$, which totals to fresh water consumption of 653,300 $m^3$ $a^{-1}$. According to the ratio specified by the Reference document on best available techniques (BREF), the fresh water consumption exceeded the upper limit by 144,900 $m^3$ $a^{-1}$.

First, the most critical departments were identified. These were:

- Brew house to worth cooling (the water balance is represented in Fig. 2.11)
- Fermentation and maturation
- Packaging
- Energy system.

In Fig. 2.12, the volume ratio of water consumed to beer sold is compared to BREF limits, good practice limits, and best practice limits. It can be seen that in all the departments the ratio is well within the BREF limits, the exception being the energy system for which the BREF limits were not given and which was also superior in terms of good and best practice limits. On the other hand, the fermentation and maturation department, as well as packaging department are considerably more troubling. Although the volume ratio of water consumption to beer sold is within the BREF limits for both the departments, it is well above the good and best practice limits.

#### 2.3.4.1 Water Minimization Opportunities Proposed

To improve the water efficiency in the brewery, the possibilities of water reuse in the packaging area were analyzed. It was established that several continuous water streams with low concentrations of contaminant were available.
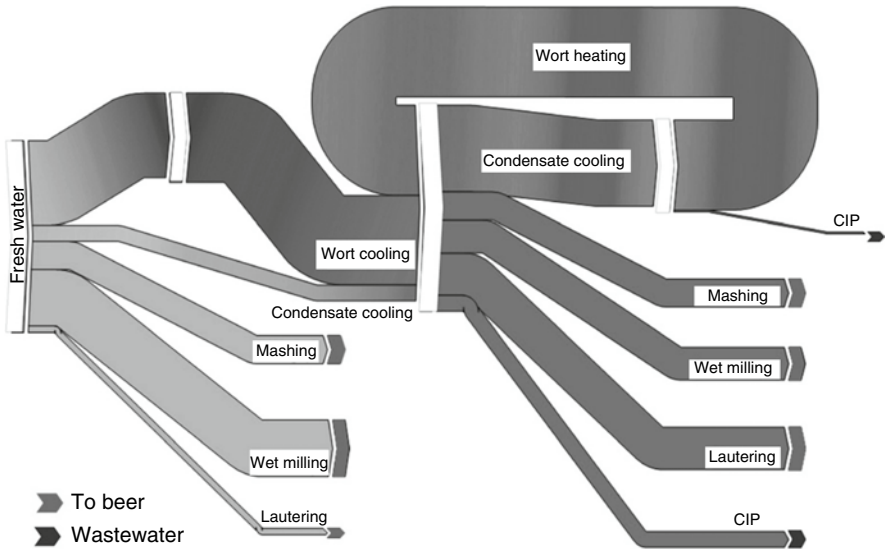
**Fig. 2.11** Sankey diagram of water balance in the brew house (Adapted from [14])
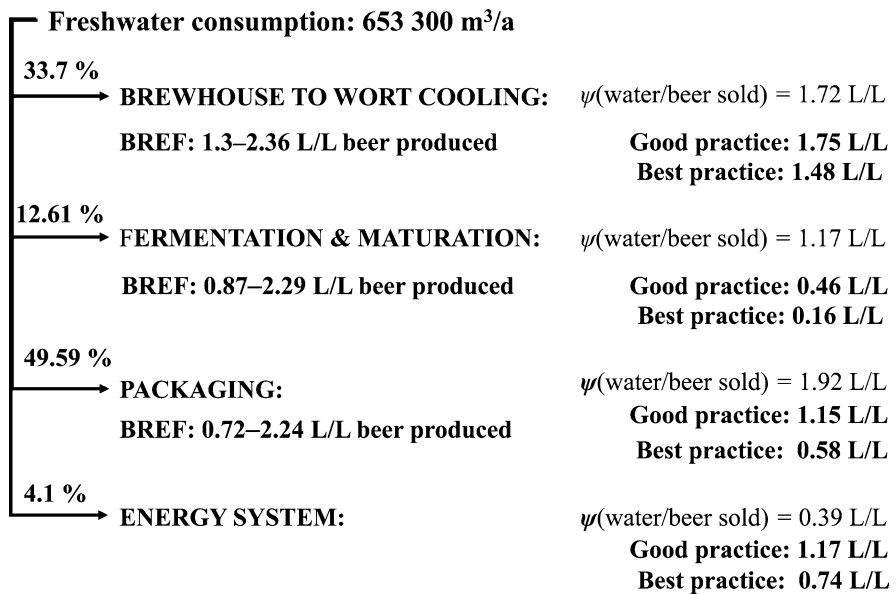


**Fig. 2.12** Identification of the most critical departments

Furthermore, the possibilities of water regeneration reuse in the brew house and the cellar were analyzed, where the direct reuse was unacceptable due to relatively high concentrations of contaminants.

The first opportunity to reduce the water consumption is to treat the wort boiling condensate with high chemical oxygen demand (COD) value. Electrolytic process based on hypo-chlorous acid and a suitable membrane separation process could be applied for the task. The treated condensate could then be reused as a rinsing water in packaging department or as a floor wash.

The second opportunity is to treat the "clean-in-place" (CIP) rinsing water (low COD value, but high conductivity value) with a suitable membrane process and reuse it in the same way as the treated wort boiling condensate.

The third opportunity was identified in the cellar, where the filter rinsing water (acceptable COD), is directly usable as a floor wash.

Finally, the fourth opportunity, if implemented, would boost the water efficiency of the already efficient energy system even further. Problem arises from the fact, that the wastewater produced needs to be cooled down before being released to the environment. At the time, this is achieved by mixing hot wastewater with cold fresh water. To satisfy the environmental temperature constraint, approximately 20,000 $m^3 a^{-1}$ of fresh water is being used for this purpose. Clearly, either mixing of the hot wastewater with a cold one, or prolonged air-cooling is the solution to this problem.

### 2.3.4.2  Economical and Environmental Benefits

By realizing the proposed solutions, the brewery could reduce its water consumption by 25% (163,300 $m^3 a^{-1}$) causing total savings of 121,600 € $a^{-1}$. All the proposed solutions are economically viable, with payback times ranging from 0.3 a to 1.4 a [14].

In addition to the water minimization, the opportunities of heat integration between batch operations were analyzed by using a mixed integer linear programming approach. The feasibilities of combined electricity, heating and cooling production were studied. The results indicate that it is possible to improve company's economic performance and reduce its environmental impact even further [15].

In the case of a trigeneration system, the highest electricity production is estimated to cover approximately 60% of the current electricity consumption. Nevertheless, due to high investment (1,173,600 €) the optimal solution selected is the cogeneration (combined heat and power) system with a back-pressure steam turbine at the pressure level of 42.4 bar. During the heating season, heat production should increase by 50% above the current level. Electricity production would cover 42% of the company's requirements. The net present value is estimated to 934,467 € and the payback period to 3.2 a.

## 2.4  Conclusion

Water is becoming more valuable and more expensive in the last years, and the forecast is even worse for the future. Some experts are talking about its comparison with oil availability and price. Therefore, much effort needs to be put into

research and development of water usage minimization in industry and in other fields of application.

The results presented in the four case studies were obtained by using the proposed water minimization strategy in conjunction with strong collaboration of experts from individual companies. The latter is always desired (read – necessary), as they possess profound and the most up-to-date knowledge for a given process. It is through this knowledge that company's process constraints can be successfully integrated in the workflow. Consequently, because the solutions obtained are tailored to the needs and demands of companies willing to improve the water efficiency, their chances of being implemented are even higher.

The results also indicate that in many cases a significant reduction in water consumption and thereby a reduction in wastewater volume can be achieved with only minor investments compared to the savings caused by a more rational water usage. The key concept for achieving this is to recognize the possibilities of direct water reuse. If such a possibility existed, it should be exploited, as this is often economically, technologically, and environmentally the most effective way for improving the water efficiency.

# References

1. Bagajewicz M (2000) A review of recent design procedures for water networks in refineries and process plants. Comput Chem Eng 24(9–10):2093–2113
2. Bogataj M, Bagajewicz M (2008) Synthesis of non-isothermal heat integrated water networks in chemical processes. Comput Chem Eng 32(12):3130–3142
3. Dunn RF, El-Halwagi MM (2003) Process integration technology review: background and applications in the chemical process industry. J Chem Technol Biotechnol 78:1011–1021
4. El-Halwagi MM, Manousiouthakis V (1989) Synthesis of mass-exchange networks. AIChE J 35(8):1233–1244
5. Foo DCY (2009) State-of-the-art review of pinch analysis techniques for water network synthesis. Ind Eng Chem Res 48(11):5125–5159
6. Jeżowski J (2010) Review of water network design methods with literature annotations. Ind Eng Chem Res 49:4475–4516
7. Krajnc D, Glavič P (2005) A model for integrated assessment of sustainable development. Resour Conserv Recycl 43(2):189–208
8. Krajnc D, Glavič P (2005) How to compare companies on relevant dimensions of sustainability. Ecol Econ 55(4):551–563
9. Kuo WCJ, Smith R (1998) Designing for the interactions between water-use and effluent treatment. Chem Eng Res Des 76:287–301
10. Linnhoff B, Flower JR (1978) Synthesis of heat exchanger networks. Part I: systematic generation of energy optimal networks. AIChE J 24:633–642
11. Linnhoff B, Hindmarsh E (1983) The pinch design method for heat exchanger networks. Chem Eng Sci 38(5):745–763
12. Smith R (1995) Chemical process design. McGraw-Hill, New York
13. Takama N, Kuriyama T, Shiroko K, Umeda T (1980) Optimal water allocation in a petroleum refinery. Comput Chem Eng 4(4):251–258
14. Tokos H (2009) Computer aided process engineering for integration of industrial processes. PhD thesis, Department of Chemistry and Chemical Engineering, University of Maribor

15. Tokos H, Novak Pintarič Z, Glavič P (2010) Energy saving opportunities in heat integrated beverage plant retrofit. Appl Therm Eng 30:36–44
16. UNESCO (2003) Water for people water for life. The UN world water development report. http://unesdoc.unesco.org. Accessed 10 Nov 2010
17. UNESCO (2010) World water resources and their use – a joint SHI/UNESCO product. http://webworld.unesco.org/water/ihp/db/shiklomanov/. Accessed 10 Nov 2010
18. U.S. Census Bureau (2010) Total midyear population for the world: 1950–2050. http://www.census.gov/ipc/www/idb/worldpop.php. Accessed 10 Nov 2010
19. Wang YP, Smith R (1994) Wastewater minimisation. Chem Eng Sci 49(7):981–1006
20. Wang YP, Smith R (1995) Wastewater minimisation with flow rate constraints. Trans IChemE A 73:889–904
21. Žbontar L, Glavič P (2000) Total site: wastewater minimisation. Wastewater reuse and regeneration reuse. Resour Conserv Recycl 30:261–275
22. Žbontar Zver L, Glavič P (2005) Water minimisation in process industries: case study in beet sugar plant. Resour Conserv Recycl 43:133–145
23. Žbontar Zver L, Petek J, Glavič P (2002) Reduction of water consumption in the textile factory. Tekstilec 45(3–4):78–83