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The role of water auditing in achieving water conservation in the process industry

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Abstract

Water has traditionally been over utilised within the process industry due to its low cost. However, increasing environmental regulations, concerns around human and ecological health, and consumer expectations of high environmental performance have placed water conservation onto the agenda of the process industry. Many conceptual and mathematical techniques are available for determining appropriate water management practices to achieve this, but these are often not easily applied in complex, multi-contaminant systems such as petroleum refineries.

This study investigated the use of water auditing techniques to examine water flows within a petroleum refinery, concurrently identifying practical ways for achieving water conservation. The work demonstrated that, even in a refinery with processes considered highly efficient within the industry, many opportunities existed to improve water conservation through technical, cultural and behavioural adaptations. These included the use of alternate water sources such as rainwater runoff, reuse of water within process units, and the introduction of an overarching company policy to minimise water use and effluent discharge. Water auditing was shown to be a simple yet effective method for exposing water management procedures which could be adopted for continual improvement, contributing to the emerging ideal practice of zero liquid discharge.

Keywords: water minimisation; water conservation; water auditing; zero liquid discharge; oil refinery; petroleum refinery

1. Introduction

Water is an important resource in industry; it functions as an essential element of processes and products, a means of heat transfer, and a medium for waste transportation (Liaw et al., 2006). Traditionally, water has been considered an abundant, cheap resource, with limited economic concerns over the volumes of water used. However, the world is facing the ongoing risk of water shortages, particularly given the uncertain impacts of climate change. Globally, industry uses approximately 20 % of the freshwater extracted by humans, around twice as much as is used for domestic purposes, and if this water is not contained within products, it exits industrial processes as wastewater (UNESCO, 2012).

Wastewater reduction and water conservation are becoming increasingly more important issues for industry, driven by stricter environmental regulations, concerns around human and environmental health, and the decreasing availability of “clean” water resources (Abu-Zeid, 1998). In order to achieve cleaner production, the process industry in industrialised countries has progressed from resistant adaptation to environmental standards, through compliance and beyond-compliance initiatives, where such offer competitive advantages (van Beers et al., 2007).

Many opportunities now exist for water conservation in industries with complex infrastructure, particularly through the use of mathematical and conceptual approaches such as water pinch analysis (Wenzel et al., 2002). However, in systems with more than one contaminant, these approaches are often difficult or impossible to apply, and require expensive and complex mathematical optimisation software (for examples see Bagajewicz, 2000; Foo, 2007). Although it is possible to include some aspects of these models into simpler water conservation approaches (e.g. Agana et al., 2013; Zbontar and Glavic, 2000), it has become clear that purely technical, mathematical approaches to water management are insufficient for achieving high levels of conservation in multi-contaminant systems. In order to be effective, water management must examine not only theoretical optimisation values, but also investigate practical, behavioural and communication issues so as to allow for a holistic approach (Seneviratne, 2007).

Water auditing is an analytical technique which quantifies water usage and quality (Seneviratne, 2007; Sturman et al., 2004) whilst simultaneously allowing for investigation into the behavioural aspects of water management. Auditing can be used to investigate water flows within refineries as a whole as well as within individual process units and operations. By quantifying flows, water auditing can determine whether significant losses are occurring within a predefined system boundary. Although some losses are unavoidable, a water management team can determine what proportion of water loss (or unaccounted for water) they are willing to accept before they need to further investigate flows and adjust water management techniques. This proportion is referred to as closure and is calculated from:

$$\text{Closure} : ((\Sigma \text{ Water Input} - \Sigma \text{ Water Output}) / (\Sigma \text{ Water Input})) < \text{Predetermined Tolerance}$$

(Sturman et al., 2004)

If closure cannot be obtained then additional investigation into water flows is necessary. Further auditing of water quantity and quality can indicate where water management can be altered so as to reduce source input and effluent output and conserve water throughout process units (ways in which water auditing can suggest improvements to water management are discuessed in American Water Works Association, 2006; Gleick et al., 2004; Seneviratne, 2007; Sturman et al., 2004).

There is an emerging drive within the process industry to maximise water conservation through zero liquid discharge (ZLD). This is the concept of closing industrial water cycles so that minimal water is injected into the system as make-up, and no water is discharged (with exceptions in some countries in cases of extreme rainfall events) (Byers, 1995). ZLD has traditionally focussed on wastewater minimisation and pollution control, however, reducing source water input by simple water and cost saving techniques can also contribute significantly to its achievement. To fully realise ZLD, industries must reduce the volume of water used by processes, prevent or remove contaminants from wastewater, and reduce the volume of wastewater output through increased reuse and recycling (Byers, 1995; Sturman et al., 2004). Wan Alwi et al. (2008) suggest this is most effectively achieved by following the water minimisation hierarchy (WMH), where water use should focus on, in decreasing priority;

1. Source elimination: Remove water requirements;
2. Source reduction: Reduce water requirements;
3. Reuse water: Reuse water directly without treatment;
4. Regenerate water: Reuse water following treatment (also known as recycling);
5. Use fresh water: When the use of ‘new’ water cannot be avoided.

Techniques such as water auditing can identify water conservation measures to be implemented following the WMH method of prioritisation, which can assist in the achievement of ZLD. These measures must be relatively straightforward to implement from both technical and managerial perspectives.

This research has investigated the use of water auditing to identify practical water conservation and effluent minimisation techniques that can contribute to ZLD in a petroleum refinery. Traditionally, water management in these refineries has focussed on contaminant removal from wastewater, driven by regulatory measures. Now that these wastewater treatment techniques are mature, the emphasis in the industry is shifting towards preventative water use approaches. However, there is still an emphasis on reducing scheme water usage, with little consideration of cheaper (e.g. bore water) or alternative (e.g. rainwater) options, and virtually no recognition of non-technical issues which may impact upon water use and efficiency (e.g. refinery culture). By conducting a comprehensive water audit of a petroleum refinery we demonstrated how water auditing can contribute to the identification of both technical and cultural measures for minimising water use and effluent discharge in the process industry, hence contributing to the achievability of ZLD.

2. Materials and Methods

A petroleum refinery south of Perth, Western Australia, was selected for this study. The refinery has an excellent reputation within the industry for its water management practices, particularly for having reduced its daily water consumption from 7 ML in 1996 to 4 ML in 2003. Water sources utilised by the refinery during the study period included scheme water purchased from the state water utility, bore water extracted on site, cogeneration steam from the adjacent power station and salt cooling water. At the time of this study the majority of water on site consisted of process flows, rainwater runoff and tank drainings, and was sent to the onsite wastewater treatment plant (WWTP) via the oily water sewer (OWS). Domestic sewage from administration buildings was sent to septic tanks.

2.1 Water auditing

The water audit methodology was based upon current industrial best practice (American Water Works Association, 2006; Sturman et al., 2004). A primary level audit was initially conducted to investigate overall refinery water inputs and outputs, with closure arbitrarily set at 10 % following Sturman, et al. (2004). A secondary level audit was then conducted to investigate the interactions between water flows in major site processes. Industrial sites are generally considered to contain three types of water; ‘process’, ‘utility’ (steam and cooling water) and ‘other’ (primarily domestic uses) (Mann and Liu, 1999), and the secondary level audit focussed on investigating each of these at various points within the refinery.

The data required for water auditing was collected through the refinery’s data management system (DM) and field studies. Flow data were collated from the DM for the 2007 calendar year. The field study component was conducted in 2008 and included site familiarization, quantification of metered flows, unmetered flows and losses, inspections and investigations of water using processes and leaks, and discussions with engineers and operators. Quantification of unmetered water flows was estimated from end uses and assumptions on the type and frequency of use.

2.2 Primary level audit

A flow diagram was prepared indicating the major water inputs and outputs of the refinery. Scheme water was measured at the refinery boundary, and bore water at the bores themselves. Cogeneration steam is purchased from the adjacent electricity utility, and hence the volume was determined from billing data. Salt cooling water is used once without treatment, so was not considered to contribute to water inputs and outputs. The refinery does not make use of rainwater runoff in its processes, and most rainwater is either sent to the WWTP (if it falls on process areas) or allowed to infiltrate. In order to assess its potential as a water source, rainwater runoff was calculated by estimating the area of impervious surfaces on site and collecting rainfall data from the Bureau of Meteorology, following Tebbutt (1998).

The volume of treated wastewater discharged to the ocean outfall is metered by the local water utility, as the refinery must pay a fee according to their discharge volumes, so was estimated from billing data. The volume of water flowing to septic tanks was estimated assuming a discharge of 120 L/d/person (European Commission, 2003), with the average number of personnel on site in 2007 being 230.

2.3 Secondary level audit

In order to conduct the secondary level audit, each of the water types were investigated at different points in the refinery. Flow diagrams were developed for the ‘process’ and ‘utility’ water case studies. ‘Process’ water was investigated in the Residue Cracking Unit (RCU) of the refinery using DM system readings from 2007 and estimating boiler blowdown to be approximately 5 % (based upon estimations provided by engineers and operators). ‘Utility’ water was assessed by investigating the steam system of the entire refinery. This included readings from the DM system from 2007, a baseline audit in 2008, extrapolation of steam audit data, and discussions and tours with the environmental team and energy and process engineers to determine where leaks were occurring. ‘Other’ water uses were investigated by an audit of the staff car wash, which involved a desktop study, manual measurements of flows, meter readings, and a video to assess the number of car washes per day and their duration.

3. Results

3.1 Primary level audit

A flow diagram was prepared to investigate the major water inputs and outputs of the refinery (Figure 1). Closure could not be obtained as unaccounted for losses amounted to 36 % of the outputs. It was evident that a more intensive water audit would be required to investigate losses within the refinery and identify potential areas for water use minimisation, reuse and recycling.

Calculations on the annual rainfall and area of the site indicated that approximately 48 % (excluding salt cooling water) of the refinery's water needs were theoretically available from rainwater runoff (Figure 2). Rainfall varies temporally throughout the year, and can be of varying quality, particularly depending on where it falls within the refinery. However, some portion of this rainfall is likely of sufficient quality for refinery uses, and may be considered as an alternative to other water sources. Even without any water efficiency improvements, reuse or recycling, this would minimise unsustainable water use from scheme, bore and cogeneration sources. In southern Western Australia this is likely a cost-effective option due to the presence of extensive unconfined aquifers which could be used for rainwater storage.

3.2 Secondary level audit

3.2.1 'Process' water

'Process' water flows were investigated at the RCU, although only major inputs and outputs were considered (Figure 3). Data for this unit was difficult to interpret because steam is not only consumed, but is also produced by this process. With the assumption of 5 % blowdown, closure could not be reached; 33 % of water losses were unaccounted for. Further investigation into DM system readings indicated that blowdown may have been as high as 13 % (with a large error range), which still did not account for enough water losses to allow for 10 % closure to be attained.

The audit of 'process' flows within the RCU indicated that several water minimisation strategies could be adopted. In this system it may be possible to cascade wash water through processes with different water quality requirements, because hydrocarbon becomes cleaner as it progresses downstream (Eble and Feathers, 1992). This requires a thorough analysis of the water quality requirements for each process, as well as the actual water quality being produced by each process step. For this refinery it is suggested that stripped sour water be used as wash water; if ammonia is low this water can be used as a make-up source for the RCU. Hydrotreatment of RCU feed is also suggested, although it is acknowledged that this may be prohibitively expensive. This would reduce sulphur emissions by up to 90 % and eliminate the need for hydrotreated mercaptane oxidation, hence reducing the volume of wastewater produced.

3.2.2 ‘Utility’ water

To investigate ‘utility’ water on site, the steam system of the entire refinery was examined (Figure 4). Flows were determined using DM system readings from 2007 and steam trap auditing data. Because each steam trap cannot be audited every year, data was extrapolated to site.

Although steam traps were regularly monitored and the register updated where leaks were occurring, leaks were only fixed during scheduled maintenance. During the audit it was noted that some leaks lost up to 10 t/d but were not repaired for as long as three years following their identification. Extrapolation of the audit data suggests that 85 t of steam may have been lost each day via steam traps. There were no records of where steam traps were directed to; the steam could be lost to grade, sent as wastewater via the OWS, or recycled via condensate return.

The audit of the steam system indicated that there were no technological barriers to reducing steam use, but given the lack, or perceived lack, of economic and cultural pressure to minimise steam use, simple conservation measures had not been introduced. Steam trap discharges are easy to minimise, but were common on site because low steam trap pressures (set by operators) require less monitoring. The current goal for the refinery’s condensate return is only 50 %, which is currently being achieved (Figure 4). However, this could be easily increased to 75 % with an accurate understanding of where steam traps discharge to and their correct operation, particularly the adjustment of steam trap pressures to their optimum value for process efficiency. To achieve this will require a cultural shift, which will need to be catalysed by a managerial push to reduce steam use.

3.2.3 ‘Other’ water

‘Other’ water uses on site were investigated through an audit of the staff car wash, which uses expensive, high quality scheme water. This audit indicated the potential for many technical and social improvements. The car wash was originally installed for staff to wash refinery waste from their cars before leaving the site, but during the audit some staff were noticed to drive through multiple times (due to its ineffectiveness), or to use the car wash only to cool the car down for their drive home. The car wash itself had a faulty sensor, leading to ‘ghost’ washes when no cars were present, and leaked excessive amounts of water to septic tanks, placing it in the lowest level of car wash efficiency worldwide (Brown, 2000). No specific employee was responsible for the car wash, so no one was tasked with reading the meter regularly.

Obvious improvements could be made to the car wash; its replacement with a 5 star car wash would save the refinery 6-7 ML of scheme water annually. Recent work also suggests that installing a system to treat and then reuse car wash wastewater can reduce water usage by up to 70 % (Zaneti et al., 2013). Installing such a system together with a 5 star car wash would further reduce the refinery's reliance on scheme water. Employee education and a cultural shift to using the car wash only when necessary may also help reduce scheme water use.

3.3 Overall results

Both the primary and secondary level water audits indicated that even though the refinery is considered to be at the forefront of water management in its industry, there were a myriad of technical, cultural and behavioural issues preventing maximum water conservation on site. Throughout the refinery there was a generally poor understanding of water use, irregular monitoring and poor record keeping.

More metering of water flows would certainly assist in achieving water closure, but, more importantly, many simple water conservation measures were absent throughout the refinery; for example, the repair of leaks in a timely manner. Major water loss incidents were often not recorded. Although these are issues of a technical nature, they are caused primarily by a misconception of the true value of water across the site.

Water conservation was considered very low priority by most employees interviewed during the audit process, and was of minimal concern compared to environmental issues driven by regulations. There were very few cultural incentives to reduce water use on site, fuelled by the misconception of considering water only in economic terms. Water is known to be underpriced economically (Gleick et al., 2004), and a lack of water conservation culture on site disregards the intrinsic environmental and social value of water, as well as embodied costs associated with high water usage, such as the energy costs inherent in heating (particularly when utilising steam), transporting and treating large volumes.

The audit identified several technical solutions that could be implemented provided sufficient cultural and behavioural change has occurred. These included a refinery-wide shift towards utilising the rainwater that falls on site, improving the water efficiency of RCU processes, repairing steam trap leaks and installing a more efficient car wash. Although the audit clearly identified that water savings could be made across the refinery, an overall estimation of potential savings could not be determined without an intensive audit of each process unit.

4. Discussion

4.1 Cultural and behavioural considerations

This study identified that where there is a lack of overarching company or government policy and structure around water conservation, cultural attitudes to minimising water use and effluent discharge may be lacking. Even where water efficiency is excellent based upon product throughput, this lack of water conservation culture can lead to significant unnecessary water losses through human error and mismanagement.

The process industry tends to focus on maximising production and minimising costs, and due to the very low economic price of water (even though it is of high social and environmental value) compared to other process and product components, minimising water use is not a primary consideration. Water costs are extremely low compared to other costs within the refinery, and the implementation of water saving techniques will generally have a much longer pay back period than simple measures aimed at increasing the productive efficiency of commercial processes. This results in significant water losses due to a focus on increasing the efficiency of feed throughput for the greatest financial return in the short term.

Given this low cultural value of water, few employees felt there was adequate incentive to minimise water use and effluent discharge at the refinery. For effective water management employees at all levels need to feel a sense of ownership or responsibility for environmental performance (Bixio et al., 2008). Without this corporate culture employees feel less inclined to exert extra effort for the sake of minimising water use. This in turn may result in a lack of monitoring and preventative or reparative action.

In order to improve water conservation in the industry, it is important that company policies provide incentives for staff to be involved in water management. Interviews conducted throughout the water audit indicated that although staff were open to the concept of improving water efficiency, they were not motivated to partake in water conservation where they did not consider it their personal responsibility. This suggests that water management is a concept that needs to be implemented throughout a refinery, and not simply by a dedicated water team within the environmental branch. The study also indicated that environmental staff were often consumed in tasks related to meeting existing environmental regulations. If these regulations were to encompass water minimisation, staff throughout refineries would likely be able to justify spending a greater percentage of their workload focussing on water management. However, it has also been noted in the past that such regulations need to carefully consider the dynamics of technical change and the risks they may pose to the economic health of industries (Montalvo Corral, 2003). If they are to be effective in reality, care must be taken before applying stringent water management regulations based upon purely environmental considerations.

4.2 Technical considerations

The water audit indicated that although most processes at the refinery were water efficient compared to world standards (European Commission, 2003), opportunities did exist for reducing water use and effluent outflow through retrofitting. This included the identification of alternative water sources such as rainwater harvesting (the modelling of such alternative sources has recently been demonstrated by Nápoles-Rivera et al., 2013), which could be stored on site within unconfined aquifers, and the potential for water cascading, where water is reused without treatment in processes with lower water quality requirements (Mann and Liu, 1999). Various tools can be used to model such opportunities highlighted by water auditing, particularly where water quality monitoring has been included (an example of such integrated water management is detailed in Agana et al., 2013).

By combining water auditing and water quality assessments, a detailed water management plan can be developed which addresses all aspects of the WMH. Such studies can identify synergy opportunities both within industrial sites and across site boundaries, leading to the establishment of industrial ecology networks which minimise both water use and effluent discharge (Lambert and Boons, 2002).

5. Conclusions

Most refineries are aware of their overall water use and effluent discharge volumes, but not how this translates to water use within individual process units (American Water Works Association, 2006; Lens et al., 2002). This study demonstrated that water auditing can be used to identify both the current weaknesses of site water management and the potential for technical and behavioural improvements, including through aligning corporate strategy with water management goals. Even where a refinery is considered world best practice for its overall water management, there exist many opportunities for water conservation on site, which could in turn contribute to the achievement of ZLD.

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Figure Captions

Figure 1: Primary water audit. Units are kL/d.

Figure 2: Rainwater flow diagram throughout the refinery. Units are kL/d.

Figure 3: Process water audit of the RCU. Units are kL/d.

Figure 4: Utility (steam) water audit. Units are kL/d.