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Towards zero liquid discharge: The use of water auditing to identify water conservation measures

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Towards zero liquid discharge: The use of water auditing to identify water conservation measures

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Abstract

Water is economically cheap, which fails to consider its intrinsic environmental and social value. However, given the uncertain future around the availability of water resources to provide industrial, environmental and social services, water conservation is now of significant concern to industries across the globe. Recently, an extension of water conservation has emerged as zero liquid discharge, whereby no water at all is released from industrial processes, regardless of its quality.

Water auditing is a tool that can be used to identify water conservation strategies, ideally leading to zero liquid discharge. This article discusses a water audit conducted on a sodium cyanide plant, where flows were determined using historical data, proxy data, and known scientific relationships. Water quality throughout the process was defined as contaminated or uncontaminated. From this simple audit, two major water conservation measures were identified and modelled which could reduce inputs and outputs by ~40%. These were the reuse of rainwater falling throughout the plant’s boundaries instead of demineralised scheme water, and the improvement of the efficiency of one of the cooling towers.

Such a methodology could be easily applied by other industries so as to improve their water conservation. The auditing method may lead to suggestions of conservation techniques for implementation either through retrofitting existing plants or contributing to the design of new ones.

Keywords: water minimisation; water conservation; water auditing; zero liquid discharge; sodium cyanide

1. Introduction

1.1 Water conservation and auditing

Water is comparatively cheap when considering the myriad of expensive infrastructure, human resources and chemical resources involved in the process industry. However, humanity is facing an uncertain future surrounding the availability of freshwater resources, ranging from pollution concerns to climate change to satisfying the water needs of a growing population (Postel, 2000). Water conservation has become a key item on the agenda of industry, and tools exist to examine how water is being used (and wasted) throughout industrial processes (Klemes et al., 2010).

Water auditing is an analytical tool which quantifies water flows and quality within a predefined boundary (Sturman et al., 2004). The technique can determine where unexpected water losses (or gains) are occurring. This assists auditors and water managers in identifying where water management
can be improved within a system (e.g. Agana et al., 2013). The initial step of any water audit is to
investigate the known overall water inputs and outputs of the system under examination. Generally an
auditor will determine prior to an audit what level of discrepancy between inputs and outputs they are
willing to accept. This tolerance is referred to as closure and is calculated from:

\[
\text{Closure} : \left( \frac{\sum \text{Water Input} - \sum \text{Water Output}}{\sum \text{Water Input}} \right) < \text{Predetermined Tolerance}
\]

(Sturman et al., 2004)

Often closure cannot be obtained, generally indicating that significant water losses are occurring
throughout the system. The method of water auditing then allows for the investigation of where these
losses are occurring throughout the system through analysing water volumes utilised by individual
process units (Sturman et al., 2004). However, it is important to note that even where closure is
obtained, this only indicates the relationship between inputs and outputs of the entire system; it does
not immediately indicate that the process is using water optimally. Further investigation into where
different source waters flow within the refinery, and where possible, their quality, assist in the
identification of water reduction measures. The work of Dakwala et al. (2009) and Zbontar Zver and
Glavic (2005) details two examples of how this can be implemented in an industrial setting.

Water auditing can thus contribute to sustainable water use, with the ideal outcome of zero liquid
discharge (ZLD). This is the concept of closing water cycles so that no water is discharged from a
system, meaning that minimal water must be input and then reused and recycled wherever possible
(Byers, 1995). Although this may seem like an impossible task, if it is seen as a best practice end goal,
it can drive innovation and achievement in water use minimisation (Lens et al., 2002). Wan Alwi et al.
(2008) suggest that ZLD is most likely to be 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.

Water auditing can be used in conjunction with the WMH to determine appropriate water
conservation measures for a particular system. By considering inputs, outputs, and water quality, ZLD
is more likely to be achieved than by focussing on minimising wastewater outputs alone.
1.2 The sodium cyanide production process

Sodium cyanide is used by industries across the globe, primarily in gold extraction, chemical synthesis and metal hardening. It is produced by mixing air, natural gas and ammonia at high temperatures in the presence of a catalyst, resulting in hydrogen cyanide gas. This gas is then mixed with sodium hydroxide, also known as caustic soda, producing sodium cyanide solution. Where solid sodium cyanide is required, excess water is evaporated from this solution and reused or treated prior to disposal. This treatment is generally through the addition of caustic soda to adjust the pH and hydrogen peroxide to destroy chemical contaminants (Rubo et al., 2003). Water is then sent for biological treatment, often in wastewater treatment ponds or wetland systems.

This study aimed to investigate the water cycle within a sodium cyanide plant in Western Australia. The plant is relatively new, having been commissioned in 1988, so was not expected to be experiencing any major water losses due to aging infrastructure. Having been built in recent decades, the proposal for the plant itself and each of its subsequent upgrades was subject to intense scrutiny by the Environmental Protection Authority (EPA) and the general public (Environmental Protection Authority, 1987, 1989, 1990a, b, 2001, 2005). During each of these assessments, the EPA highlighted the need for stringent wastewater quality requirements, due to the flow of wastewater to the marine environment (Environmental Protection Authority, 1987, 1989, 1990a, b, 2005). However, only in one instance did the EPA suggest that the volume of such flows could be reduced by recycling or reusing wastewater within the process, and this was not mandated under the license agreement (Environmental Protection Authority, 2001). As such, most of the focus at this site has been on reducing the concentration of contaminants leaving the plant, with little consideration of the volume of water entering and leaving. The impetus has been heavily placed on compliance with pollution regulation, not on water conservation.

Such a focus has been a common trend in industry until recently, where the emphasis has had to shift to using the WMH to reduce both inputs and outputs of processes, with particular efforts towards reuse and recycling (Byers, 1995). The plant in this study does recycle contaminated water, which reduces overall water inputs and outputs. However, scope may exist to reduce these further, with the ultimate goal of ZLD, and this study aimed to determine the feasibility of this by examining the quantity and quality of flows throughout the plant.

2. Materials and Methods

2.1 Audit site
A sodium cyanide plant, part of a larger chemical production facility located in south-west Western
Australia, was selected for this study. Sources utilised by the plant during the study period included
scheme, rain, bore and demineralised scheme water, as well as water contained within the caustic
soda, hydrogen peroxide, sulphuric acid and copper sulphate used in the process. Water used within
the plant is sent to onsite wetlands, aerobic treatment units or offsite disposal, lost through
evaporation, drift, evapotranspiration or infiltration, or leaves the site in the chemical product.

2.2 Water auditing

The water audit methodology was based upon current industrial best practice (American Water Works
Association, 2006; Sturman et al., 2004). A flow diagram of primary water flows across the site was
prepared. Diagrams representing the three types of water used in industry; ‘process’, ‘utility’ (steam
and cooling water) and ‘other’ (in this case, amenities and emergency response) (Mann and Liu, 1999)
were also prepared to identify where flows were directed across the site. A fifth diagram was prepared
to investigate flows to the onsite water treatment wetland.

The water audit was conducted using historical data from February 2012 to January 2013. Wherever
possible, data from flow meters was analysed, although for several points in the process this was not
possible, and flows needed to be estimated using proxy data (for example, rainfall from the nearby
weather station) or calculated based upon known relationships (for example, evaporation from the
cooling towers). The methods used to determine each flow are detailed in Table 1. All flows were
determined on the daily timescale, averaged over a one year period.

Following the collection of flow data, it was determined whether closure could be reached for the site,
with closure arbitrarily set at 10 % following Sturman, et al. (2004).
Table 1: Methods of measuring, calculating and/or estimating water flows

<table>
<thead>
<tr>
<th>Flow</th>
<th>Method of measurement/calculation/estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
</tr>
<tr>
<td>Scheme water</td>
<td>Metered, although some months could not be included in the model because meters had reached their maximum during the month and needed to be reset</td>
</tr>
<tr>
<td>Rain water</td>
<td>Rainfall measured by the Bureau of Meteorology at the nearby Medina Research Centre, and the volume falling on site estimated from areas calculated using site drawings</td>
</tr>
<tr>
<td>Caustic soda</td>
<td>Metered</td>
</tr>
<tr>
<td>Demineralised scheme water (steam)</td>
<td>Metered, although some months could not be included in the model because meters had reached their maximum during the month and needed to be reset</td>
</tr>
<tr>
<td>Bore water</td>
<td>Metered, although some months could not be included in the model because meters had reached their maximum during the month and needed to be reset</td>
</tr>
<tr>
<td>Hydrogen peroxide</td>
<td>Metered</td>
</tr>
<tr>
<td>Sulphuric acid</td>
<td>Metered</td>
</tr>
<tr>
<td>Copper sulphate</td>
<td>Metered</td>
</tr>
<tr>
<td><strong>Internal flows</strong></td>
<td></td>
</tr>
<tr>
<td>Rainfall to bunded areas</td>
<td>Calculated using rainfall from the Bureau of Meteorology. Areas calculated using site drawings, and assuming that all rainfall becomes runoff (i.e. no standing water)</td>
</tr>
<tr>
<td>Rainfall to unbunded areas</td>
<td>Calculated using rainfall from the Bureau of Meteorology. Areas calculated using site drawings, and assuming that all rainfall becomes runoff (i.e. no standing water)</td>
</tr>
<tr>
<td>Rainfall to vegetated areas</td>
<td>Calculated using rainfall from the Bureau of Meteorology and areas calculated using site drawings</td>
</tr>
<tr>
<td>‘Stormwater’ (rainfall from unbunded areas + boiler blowdown + cooling tower blowdown)</td>
<td>Metered</td>
</tr>
<tr>
<td>‘Effluent’ (wastewater from the process + rainfall from bunded areas)</td>
<td>Metered</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td></td>
</tr>
<tr>
<td>Aerobic Treatment Units</td>
<td>Estimated assuming each person on site produces 120 L of wastewater per day (European Commission, 2003), with an average attendance on site of 81 people per day</td>
</tr>
<tr>
<td>Offsite disposal</td>
<td>Cannot be metered or estimated</td>
</tr>
<tr>
<td>Infiltration</td>
<td>Calculated assuming an evapotranspiration factor of 0.8 (estimated by Water Corporation, 2008), and assuming that the rainfall on vegetated areas that is not evapotranspired infiltrates to groundwater</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>Calculated assuming an evapotranspiration factor of 0.8 (estimated by Water Corporation, 2008) for rainfall falling on vegetated areas</td>
</tr>
<tr>
<td>Product</td>
<td>Calculated based upon the volume and concentration of liquid cyanide leaving the plant</td>
</tr>
<tr>
<td>Wetlands</td>
<td>Metered (sum of ‘stormwater’ and ‘effluent’)</td>
</tr>
<tr>
<td>Drift</td>
<td>Estimated assuming a drift of 0.375 % from cooling towers (Sturman et al., 2004).</td>
</tr>
<tr>
<td>Evaporation</td>
<td>Estimated for the two cooling towers. An evaporation factor of 0.8 was assumed (Seneviratne, 2007). Cooling Tower 1 has a circulation rate of 1500 kLh(^{-1}) and a temperature increase of 13 °C, and Cooling Tower 2 a circulation rate of 1300 kLh(^{-1}) and a temperature increase of 5 °C. This data was used in the following equation to estimate the evaporative loss:</td>
</tr>
<tr>
<td></td>
<td>Evaporative loss = (Evaporation factor x Water circulation x Temperature differential x Specific heat of water) / Latent heat of vaporisation of water</td>
</tr>
</tbody>
</table>

3. Results

The audit of the primary flows (Figure 1) indicated a difference between inputs and outputs of 0.7 %. This primary audit did not include outputs to offsite disposal as they could not be metered or estimated, although they were anticipated to have accounted for a very small proportion of total water outputs. Evaporation from the cooling towers was the major output from the plant, accounting for 51 % of the total.
Figure 1: Primary flows of the sodium cyanide plant. All values are kLd⁻¹. Demin represents demineralised scheme water. H₂O₂, H₂SO₄ and CuSO₄ represent the aqueous hydrogen peroxide, sulphuric acid and copper sulphate added to the process effluent for destruction of chemical contaminants. ATUs represents aerobic treatment units.

An investigation of ‘process’ water flows revealed that all of the water inputs to site contribute to the water used in the sodium cyanide manufacturing process (Figure 2). However, discussions with site engineers indicated that, in general, scheme, rain and bore water are only included in the process once they become contaminated from contact with process areas (i.e. bunded areas). Instead of treating these streams to improve water quality, it is assumed they contain low concentrations of cyanide, and they are thus included in the process as make-up water.
Figures 2, 3, and 4 illustrate the water flow processes on site. Investigations into 'utility' and 'other' uses indicated that 'utility' flows are provided from bore and demineralised scheme water (Figure 3) and 'other' flows from scheme water (Figure 4).
Investigating which water inputs were directed to ‘process’, ‘utility’ and ‘other’ flows enabled us to infer the quality of water entering each unit on site without requiring water quality testing.

Following the collection of data for the primary audit, it was decided that it would be interesting to further investigate the flows being sent to the treatment wetlands (Figure 5). This is metered as two separate flows; ‘stormwater’ and ‘effluent’. ‘Stormwater’ represents flows that have not been contaminated by cyanide, including rain that falls on unbunded areas, and boiler, reactor and cooling tower blowdown, averaging 293 kLd\(^{-1}\). ‘Effluent’ represents flows that have potentially been contaminated by cyanide, including rain that falls on bunded areas and wastewater from the sodium cyanide production process, as well as any chemicals added to treat the water (caustic soda, hydrogen peroxide and sulphuric acid), averaging 315 kLd\(^{-1}\).

Figure 5: Water flows that eventuate in the treatment wetlands. All values are kLd\(^{-1}\).

4. Discussion

4.1 Data quality and closure

Closure was reached during the primary audit, indicating that most of the major flows throughout the plant could be accounted for. It must be considered that several of the flows in the primary audit were not metered, but were calculated or estimated, meaning their accuracy is questionable. The 0.7 % difference between inputs and outputs is very small; in a similar study of a petroleum refinery the auditors could not account for 36 % of water outputs (Barrington et al., 2013). This small difference
should be accepted with caution, as there may be losses within the system which were overlooked through under- or over- estimations of flows that were not metered. However, in general, such a small difference between inputs and outputs indicates sound knowledge of flows on site, and demonstrates that when flows are not metered, estimates can still be made on the basis of proxy data and known scientific relationships.

4.2 Replacement flows

Knowledge of where water was flowing across the site allowed for further investigation into how inputs and outputs could be reduced. It was observed that a large volume of contaminated scheme, bore and rain water is currently recycled within the process rather than being sent directly for treatment (Figure 1). Despite using the contaminated water in the process, 204 kLd$^{-1}$ demineralised scheme water was still required. A large volume of uncontaminated rain, bore and demineralised scheme water (‘stormwater’, 293 kLd$^{-1}$) is not used in the process and is sent directly to the treatment wetlands (Figure 5). It may thus be possible to replace demineralised scheme water inputs with this uncontaminated ‘stormwater’. Examining water quality to reduce water inputs or redirect flows is beginning to be used in various industrial plants (e.g. Alvarez et al., 2004).

A large volume of rain water is also lost to infiltration and evapotranspiration via the vegetated areas on site. Were these vegetated areas converted to capture runoff, the area could harness an additional 60 kLd$^{-1}$. However, as 204 kLd$^{-1}$ demineralised scheme water is currently required for the process, and ‘stormwater’ from the current site configuration could provide 293 kLd$^{-1}$, it may be unnecessary to remove these vegetated areas. An impediment to using rain water as an input is the temporal distribution of rainfall, particularly at the location of this plant, which experiences distinct wet winters and dry summers. In order for rainfall to be considered a viable water input throughout the year, rain water must be stored during wet periods and extracted when necessary. The location of this plant gives the company a distinct advantage in this regard, as it overlies an unconfined aquifer which could be used for water storage. Mathematical models exist to assist companies in determining how they can best harness and store alternative, temporally varying flows such as rainfall (Nápoles-Rivera et al., 2013).

Given the high quality water required for the process, the ‘stormwater’ would require treatment before replacing the high quality demineralised scheme water flow, which would undoubtedly incur costs. However, if the aim is water conservation leading to ZLD, this option may be appropriate.
4.3 Improving efficiency

Whilst conducting the audit it was identified that the evaporation from the two cooling towers on site accounted for 51% of the water outputs. Although evaporation is commonly a major output of industrial processes (Seneviratne, 2007), the auditors felt there could be scope for decreasing the high proportion at this plant. Further investigation indicated that although the cooling towers had similar flow through rates (Cooling Tower 1: 1500 m$^3$h$^{-1}$, Cooling Tower 2: 1300 m$^3$h$^{-1}$) and heat loads to remove, Cooling Tower 1 was much less efficient, losing three times as much water to evaporation compared to Cooling Tower 2. For the sake of water conservation, the efficiency of Cooling Tower 1 should be improved, although it is noted that this may incur substantial costs. It may be more practical to note where and why the inefficiencies are occurring that result in this large difference so as to avoid a similar situation when designing and installing future plants.

4.4 A simple water conservation model

Currently, the plant receives inputs and produces outputs of approximately 1800 kLd$^{-1}$. If all ‘stormwater’ flows were instead input to the process, replacing demineralised scheme water inputs (Figure 6), total inputs and outputs could be reduced by approximately 10%. If Cooling Tower 1 were to operate at a similar efficiency to Cooling Tower 2, both inputs and outputs of the plant could be reduced by approximately 25 – 30%.

If ‘stormwater’ flows were used to replace demineralised scheme water inputs and the efficiency of Cooling Tower 1 were improved to be similar to that of Cooling Tower 2, inputs and outputs across the site could be reduced by approximately 40%. Over a one year period, this would amount to a water input and wastewater output reduction of the order of 400 ML.
5. Conclusions

This study used historical data and inferences from proxy data and known scientific relationships to conduct a site-wide water audit. The audit was relatively straightforward, and identified water conservation techniques which could reduce overall inputs and outputs by up to 40%. Although measures such as improving cooling tower efficiency would likely incur significant financial costs, there may be scope to implement some measures with short payback periods. For more expensive conservation approaches, consideration must be given to the financial costs of implementation, particularly the costs and energy involved in water treatment, compared to the benefits of water conservation.

This methodology could be applied to many industrial processes, particularly as it does not require historical meter data for each individual flow. Such audits could assist in identifying conservation measures that could be retrofit to existing plants. Water auditing of existing processes also provides a service to companies commissioning new plants, as water conservation measures which may be prohibitively expensive for retrofitting may be suitable if considered in the initial stages of design.

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Figure Captions

Figure 1: Primary flows of the sodium cyanide plant. All values are kLd^{-1}. Demin represents demineralised scheme water. H_{2}O_{2}, H_{2}SO_{4} and CuSO_{4} represent the aqueous hydrogen peroxide, sulphuric acid and copper sulphate added to the process effluent for destruction of chemical contaminants. ATUs represents aerobic treatment units.

Figure 2: ‘Process’ water flows. Figure 3: ‘Utility’ water flows.

Figure 4: ‘Other’ water flows. Figure 5: Water flows that eventuate in the treatment wetlands. All values are kLd^{-1}.

Figure 6: ‘Process’ water flows if ‘stormwater’ replaced demineralised scheme water inputs.
Highlights: Barrington and Ho 2013

1. Multiple methods can be used to determine historical flows in water audits
2. Water auditing indicates areas for conservation, such as alternative water sources
3. Results of water audits can inform both plant retrofits and new infrastructure
4. Water auditing contributes to achieving zero liquid discharge