Toxic Substance Accumulation Prediction: A Useful Addition to Conventional Life Cycle Assessment When Comparing Water Recycling Technology

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Abstract: One aspect of decision making in water recycling is the need to evaluate the environmental performance of different treatment technologies. Life Cycle Assessment (LCA) is identified here as a suitable initial tool that can be used to address a wide range of potential environmental impacts caused by each technology under study over their life-time. In this paper, the results of a case study in which LCA is used in evaluating three water recycling technologies are reported. One of the findings from the case study is that LCA fails to account for the potential accumulation of toxic substance which is a major concern in water recycling, particularly when applications such as irrigation are of interest. A Toxic Substance Accumulation (TSA) prediction method is described which was tested with the same treatment technologies assessed in the LCA case study. The information on land use impacts obtained from the LCA study including Terrestrial Ecotoxicity Potential (TETP) and Salinisation Potential (SP) is compared with the information derived from the TSA method. It is found that the additional information obtained from the TSA method adds value to the environmental impact assessment of water recycling at both process and policy making levels and also assists in addressing the issue of sustainability of water recycling practice.

Keywords: *Water recycling technology, Life cycle assessment, Toxic substance accumulation*

1. INTRODUCTION

Life Cycle Assessment (LCA) has been shown to be useful in comparing different products or processes based on their environmental performance (Guinee et al., 2001). LCA has also been found to be an appropriate tool in assisting in evaluation of water recycling technologies as it offers a holistic assessment of the potential environmental impacts caused by all life stages (construction, operation, and demolition) of each technology under study. A wide range of environmental impacts is included in LCA including global warming, eutrophication, ecotoxicity, and human toxicity. Both quantitative and qualitative impacts can be derived from the study.

In this paper, approaches to evaluating the environmental performance of water recycling technologies are discussed. LCA was used as an initial tool to compare three different water recycling trains (a treatment train contains a number of treatment unit processes) each consisting of different technologies.

One of the findings from the case study is that more information is necessary if ecological sustainability in water recycling is to be addressed. With regard to the land use impacts, LCA has an ability to predict potential impacts of terrestrial ecotoxicity and soil salinity. It fails, however, to account for the potential long term impact of accumulation of toxic substances introduced to land by the practice of water recycling. Prediction of the extent of toxic substance accumulation in the long term is important from an ecological perspective. It is also important from a human health perspective given the potential for accumulation of toxins in foodstuffs. Prediction of future impacts should also be recognised to be a key to sustainability of current practice. This will provide vital information for environmental decision making at both the process and policy making levels. For example, a predicted unacceptable level of toxic substance accumulation may suggest that pollution control at source is required in order to lessen the pressure on the environment and, at the same time, lessen the efforts (e.g. energy input and chemical load) needed to remove toxic substances in wastewater treatment.

In this paper, we propose an additional toxic substance accumulation prediction feature based on the technique of fate modeling to be undertaken as a separate desktop assessment together with LCA. A toxic substance accumulation prediction can be developed in which a group of substances are examined and the accumulation of this group is forecast over different timeframes (e.g. 20, 50, 100 years) based on explicit estimations of partition coefficients using a fate modelling software called 'ChemCAN' developed by Mackay et al. (1997).

This paper begins by stating the needs for taking into account toxic substance accumulation in the sustainable water recycling context. The proposed method is tested in the LCA case study. Comments are provided on the value the proposed method brings to environmental decision making in water recycling.

2. IMPLEMENTING ENVIRONMENTAL LCA IN WATER RECYCLING – CASE STUDY

2.1 Goal and Scope Definition

The objectives of this study are: 1) to investigate the potential environmental impacts associated with different wastewater treatment technologies for a specified water recycling application; 2) to recommend how to improve the environmental performance of each train where it is possible; and 3) to identify roles and limitations of LCA in water recycling.

The functional unit for this case study is "1 ML of recycled (treated) water from a centralised treatment plant in a greenfields site to be used for agricultural food production irrigation purposes". By specifying the application of product water, it is assumed that all recycled water is to be applied onto land. It is also assumed that all treatment technologies considered in the case study are technically capable of producing recycled water of the quality equal to or better than that specified in the guideline for using recycled water for food production irrigation purposes. The guidelines for sewerage systems and use of reclaimed water requires the use of tertiary treatment to achieve thermotolerant coliform levels <10 cfu/100ml (ANZECC, 2000). Additionally, given that dryland salinity affects some 2.2 million hectares of land in Australia and is partially due to water logging and severely damaged irrigated soils (Feitz and Lundie, 2002), it was necessary to incorporate an indicator that captured this feature of land use in the technologies under study.

Treatment technology 1: Membrane bioreactor (MBR) + Reverse Osmosis (RO)

The technology of using MBR followed by RO (hereinafter referred to as the MBR system) is considered to be an advanced wastewater treatment option offering a high level of treatment although at present incurring a high cost. A pre-treatment step is required prior to feeding the wastewater to the MBR unit. The MBR's common features include the use of microfiltration membranes. The membrane unit can be directly immersed into the reactor where the biological treatment takes place; the outside-in filtration mode is operated under negative pressure, and renewal of the biomass to be filtered is undertaken by airlift-induced flow (Cote et al., 1997).

Treatment technology 2: Conventional primary, secondary, tertiary + CMF + Ozonation

This treatment train makes use of conventional treatment up to tertiary level (sand filtration) and includes a polishing step involving ozone pretreatment, microfiltration (CMF) and chemical disinfection (this system is hereinafter referred to as the CMF system). The wastewater treatment plant at Rouse Hill in Sydney uses a process very similar to the CMF system described above (Engelbrecht, 2001). It should be noted that the purpose of the Rouse Hill recycling scheme is to produce recycled water suitable for urban reuse applications (particularly toilet flushing and garden irrigation). Analysis of a system similar to that at Rouse Hill system is included here in order to test whether producing a higher effluent quality than required for irrigation purposes has any benefits which can be interpreted using LCA.

Treatment technology 3: Waste stabilisation pond system

A common Waste Stabilisation Pond (WSP) system consists of three types of ponds; anaerobic pond, facultative pond, maturation pond. In this system, chlorine disinfection is added after the maturation ponds for the purpose of removing pathogens to a level that meets the guidelines for use of reclaimed water for the purposes mentioned above (ANZECC, 2000). WSP systems represent basic technology but possess a range of advantages including flexibility and ease of design, simplicity and low cost of construction, operation and maintenance (Pearson, 1996). Because of these advantages, it is included in the study in order to evaluate its environmental performance. However, it should be noted that the use of WSP is only feasible for a greenfields site with no land restrictions. In this case study, a conventional pond system is considered and typical performance of the system is assumed (Metcalf & Eddy Inc., 1991).

2.2 Inventory

System boundaries

The system boundary covers the operational phase of the treatment train. The operational phase includes the production of chemicals consumed in the treatment processes, the production of energy consumed throughout the treatment processes, the treatment of sludge and application of biosolids, and the application of recycled water for irrigation purposes. System boundaries were extended to include all unit processes in order to maintain functional congruence with the MBR option that involves secondary treatment, and the removal of metals in advanced recycling treatments.

Data collection

Data used in the case study has been gathered from a number of literature sources including text books, journals, electronic sources, and unpublished research. In addition, field data was obtained for the CMF system. For the MBR and WSP systems, the data used to assess this treatment train was mainly derived from a number of published sources of literature. For the CMF system, field data was obtained from the Rouse Hill water recycling plant and other data obtained from literature sources.

2.3 Life Cycle Impact Assessment Results

The following results are very specific to a set of assumptions made in this case study. This includes the assumption for the CMF system; all the trace elements removed by secondary treatment and membrane processes were combined in the sludge which in turn was treated to produce biosolids. For the MBR system, it was assumed that all trace elements removed by the RO unit were placed in landfill. The results reported here should therefore not be generalised to represent the environmental performance of these treatment technologies under all conditions. The major potential environmental impacts for the water recycling case study considered here (using LCA) are Global Warming Potential (GWP), Terrestrial Ecotoxicity Potential (TETP), Human Toxicity Potential (HTP), Freshwater Ecotoxicity Potential (FAEP), Marine Ecotoxicity Potential (MAETP) and Eutrophication (EP) (Weidema, 1997). The Equivalency Factors (EFs) in use have been modified for Australian conditions (Lundie et al., 2001). The log-scale normalised impacts for each treatment train are shown in Figure 1. The normalisation is done against Sydney data. Under the same scale, TETP dominates other normalised impacts. Due to high variation of the results, log-scale is used in plotting the normalised impacts.

The observed result of very high level of TETP is due mainly to the combined energy consumption and the application of biosolids on soil (the most common application for biosolids in Australia).

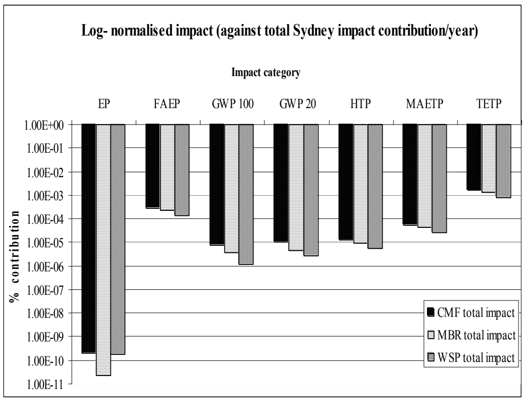

Figure 1: Selected normalised potential impacts

The quality of the sludge used in biosolids application is the main factor influencing performance under the FAEP and the HTP impact categories. The quantification of energy consumption is reflected under the GWP impact. MBR and CMF both consume high energy.

In this case study, a new salinisation potential (SP) developed by Feitz and Lundie (2002) has been adopted to predict the suitability of applying recycled effluent produced by different treatment trains on Australian red-brown soils. This is a local impact category and specific Australian specific conditions are assumed. The sodium concentration (Na^+) is indicative of an ability to remove ions from the influent by each treatment train. From

Table **1**, the WSP train has a high SP value which means that the recycled water produced by WSP has a higher potential to cause salt accumulation on soil than other trains. However, salt accumulation is not the only concern under this impact category. Effect on soil structure caused by different types and amount of ions present in the irrigation water is also important. A relationship has been established between the Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC) (Feitz and Lundie, 2002). In

Table **1**, the predicted effect on soil structure as a result of applying different quality irrigation waters on soil is derived from the SAR and EC relationship.

Table 1: Salinisation potential and effect on soil structure of different irrigation water

Irrigation water - source	SP (kg Na+ - equiv) /ML	Effect on soil structure based on the SAR & EC relationship
CMF system	17.48	Unlikely to cause permeability hazard
Stabilisation pond (WSP)	140.63	Potentially cause soil dispersion
MBR system	9.13	Likely to cause soil dispersion

The MBR system has a very low SP value which means that the use of the recycled water produced from this train is unlikely to cause salt accumulation on land. However, the effect on soil structure based on the SAR and EC relationship of the MBR recycled water shows that it is likely to cause soil dispersion. This is undesirable as the soil will lose its ability to hold nutrients and water and hence is not suitable for agricultural use. The reason the MBR system produces irrigation water that can cause soil dispersion arises because the RO unit is particularly effective in removing ions from the water leaving the water harmful to soil structure. RO exhibits an 80-98% removal rate of ions such as sodium, calcium, and magnesium whereas the WSP and CMF have negligible removal rates of major ions.

The best treatment train under this impact category is the CMF system as it has a low SP value and unlikely to cause permeability hazard.

3. PROPOSED TOXIC SUBSTANCE ACCUMULATION (TSA) PREDICTION METHOD

3.1 Method

The concept of fate modeling is adopted in order to predict the accumulation of toxic substances. The intention here is to focus on a list of elements considered to be of concern if levels are elevated in the agricultural soil. The partition coefficients (coefficients for describing partitioning behaviour of metals in the environment) are estimated using the ChemCAN model (Mackay et al., 1996). The proposed TETPs to predict the accumulation of toxic substances are as follows:

1. Construct a list of those toxic substances that are not biodegradable (Hauschild and Wenzel, 1998), commonly found in wastewater, and of concern at high accumulated levels in agricultural soil.
2. Estimate the amounts of each substance that end up in soil as the final compartment based on fate modeling. The software 'ChemCAN' (Mackay et al., 1996) has been applied with regional environmental data of New South Wales, Australia used where available (Australian Bureau of Statistics, 2000). Where the regional data is not available, the generic data provided in the software is assumed. Substance-specific parameters are assumed to be the same as those used in USES-LCA (Huijbregts, 1999).
3. From the 'ChemCAN" model outputs, the fraction of toxic substances remaining in the soil are calculated. In the case of cadmium, the above result shows that 95.4% of the amount emitted to soil will stay in the soil. Note that the persistence result as it appears in the model output is the time it takes for a substance to reach its equilibrium state. This does not reflect the biodegradability of a substance. TSA can be calculated as follow:
   TSA_{50yrs} of A (kg) = Initial emission of A to soil (kg/d) * Fraction of A stays in the soil *(50 * 365)- Crop uptake and leaching[a]

   [a]This factor has not been incorporated in the results shown in this paper.

3.2 Results

Using the TSA prediction method described above, results have been obtained and compared with the soil cumulative contaminant loading limit (CCL) triggers for heavy metals found in the Australian Water Quality Guidelines for Fresh and Marine Water (ANZECC and ARMCANZ, 2000). The CCL is the trigger value for contaminant concentration in soil in kg/ha. It indicates the cumulative amount of contaminant added, above which further thorough site-specific risk assessment is recommended if irrigation and contaminant addition is continued.

Figure 2 shows the TSA results of each train together with the suggested soil CCL values.

4. COMPARISON OF LAND USE IMPACT RESULTS OBTAINED FROM CONVENTIONAL LCA WITH THE PREDICTED TOXIC SUBSTANCE ACCUMULATION (TSA) RESULTS

4.1 Recommendations Based on LCA Results

From the LCA case study reported in Section 3, the land use impacts are TETP and SP. According to the TETP results, it is recommended that the CMF train should consider heavy metal removal from biosolids prior to land application.

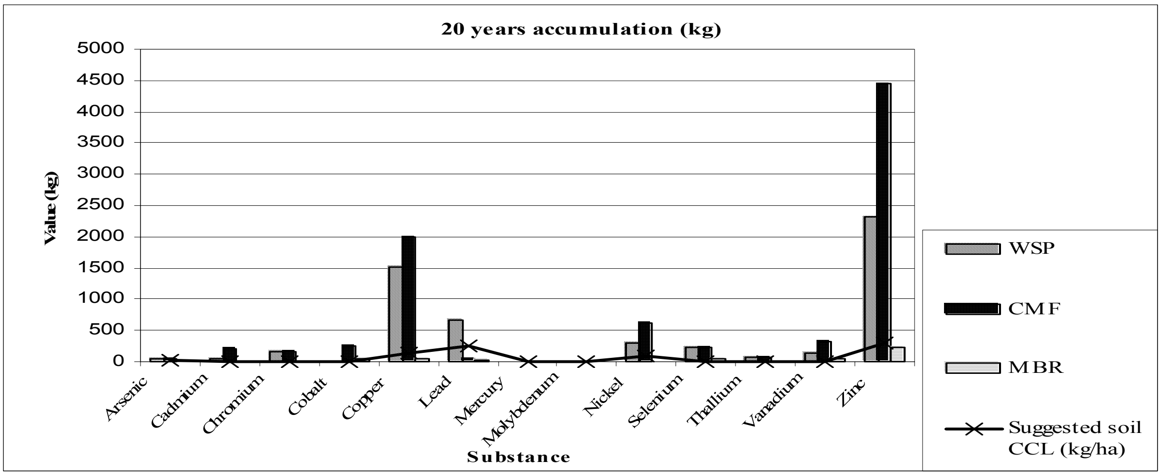

Figure 2: Predicted accumulation of toxic substances of different trains

This is because heavy metals (and beryllium) contained in the biosolids from this process are the main contribution to its high TETP.

According to the SP results, it is recommended that replacing the RO unit found in the MBR train with other suitable unit processes will improve its performance under the SP category. This is because the RO unit is too effective in removing ions with resultant detrimental effects on soil structure (as discussed earlier). In terms of the quantitative SP results in kg Na^{+}-equi/ML, all treatment trains produce effluent of acceptable quality for irrigation purposes. While the effluent produced from CMF and MBR trains are suitable for crops ascribed to have a 'very sensitive' level of tolerance, the effluent produced from the WSP train is only suitable for crops considered to have a 'sensitive' level of tolerance as defined in the irrigation water guidelines (ANZECC, 1992).

4.2 Recommendations based on the proposed TSA prediction results

The following recommendations are provided based on the predicted TSA results for each system. (Note that these recommendations have not taken into account the toxic substance emissions from other sources imposed on the receiving land of concern; for example, cadmium emission on land may also come from sources such as fertilizers).

- Both WSP and CMF treatment trains are not appropriate for the irrigation application in the timeframe of 20 years if their treated effluent and biosolids are to be applied onto land with the total area less than 1 ha.
- The zinc value of both trains since our results indicate that zinc is the limiting factor for the irrigation application in this case).
- With a longer timeframe, it is critical that the receiving areas continue to be expanded in order to avoid causing soil toxicity. For example, if a 100-year timeframe is of interest then the area of land used for the application of the treated effluent and biosolids must be 5 times larger than that calculated for 20 years.
- In order for the WSP and CMF trains to be acceptable for the irrigation application with a 20-year timeframe, the treated effluent and biosolids need be spread over land with a total area of no less than 8 ha for WSP and 15 ha for CMF (this calculation is based on
- Since land is limiting it is impossible to keep spreading these heavy metals indefinitely, therefore an action of reducing the use of heavy metals at source needs to be considered if sustainability is to be achieved. This is likely to be an important recommendation at the policy level.

5. CONCLUSION

A wide range of potential environmental impacts, mostly of global focus, is included in LCA. This renders LCA a suitable first tool for environmental assessment of water recycling technology as it provides an overview of different potential environmental impacts caused by a particular water recycling practice over its life-time. The results derived from LCA can also assist in highlighting the particular environmental issue of concern. For example, in the case study presented in this paper, the TETP is identified as the most serious environmental impact arising from implementation of the water recycling treatment trains under consideration A new impact category, SP, brings additional value to the current LCA in that it provides a site-specific environmental impact on land. We believe that inclusion of this impact category is critical when examining water recycling strategies from a sustainability perspective

Additionally, the new TSA prediction proposed here is designed to add value to the environmental assessment of water recycling especially when an irrigation application is a possibility. The information derived from the TSA prediction can be useful at both the treatment process and policy making levels. At the process level, recommendations can be provided as to the identity of the substance (or substances) likely to be limiting with respect to irrigation application. Insight into the area of land to which effluent and biosolids must be applied in order to prevent soil toxicity can also be derived from such an analysis. At the policy making level, the LCA analysis may highlight the need for source control of toxic substance generation if sustainable development is to be maintained.

The work presented here is a part of an on-going PhD study. Further research plan encompassed in the PhD include extending the use of MFA for policy decision making level of water recycling. The iterative interaction between the use of MFA and LCA at different levels of decision making will then be developed.

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