Quantitative systems analysis as a strategic planning approach for metropolitan water service providers

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Abstract Sydney Water selected life cycle assessment (LCA) to inform a review of its overall strategic planning document: WaterPlan 21. This assessment covered the entire business and has enabled ecological sustainability to be assessed in terms of quantitative indicators. The LCA was performed by firstly examining a base case which would eventuate if Sydney Water maintained its current operations with only the modifications, augmentations and upgrades planned for implementation between now and 2021. We then performed a number of scenario analyses to examine the benefits of additional demand management, energy efficiency, energy generation, supply augmentation and effluent quality initiatives. The results indicated significant improvements are available and that some of these measures are more desirable than others. We also examined a scenario for the alternative delivery of water and wastewater services in new urban areas. This showed quantitatively that, since connecting new fringe suburbs to the existing system requires significant expenditure on energy for pumping, major improvements in the sustainability of water and wastewater systems can be achieved by using localised, water-saving alternatives.

Keywords Life cycle assessment; water; wastewater; sewage; biosolids; greenfield sites

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Introduction

Sydney Water is required to conduct its operations in accordance with the principles of ecologically sustainable development, according to the *Sydney Water Act*, 1994. According to the *Protection of the Environment Administration Act*, 1991, this requires "…effective integration of economic and environmental considerations in decision-making processes". WaterPlan 21, Sydney Water's long-term strategy for service provision, is being reviewed to bring it up-to-date with developments in the organisation and its operating environment since it was written five years ago. The review is an important decision-making process and therefore the process required some kind of technical environmental planning tool to complement the economic and financial assessments. Sydney Water has previously employed Life Cycle Assessment (LCA) for strategic environmental assessment of alternative options (e.g. Peters and Lundie, 2002). LCA is a tool more holistic, quantitative, comparative and predictive than the few alternatives available for comparing alternative technical systems for delivery of Sydney Water's services in 2021 on the basis of their ecological sustainability. While a few other tools exist (e.g. Sustainable Development Records; see Tillman *et al.*, 1997) there are very few other alternatives that are as comprehensive and that have had as widespread use in the environmental design profession.

The LCA examined the relative potential environmental outcomes under different future scenarios, representing a base case ("business as usual") and several different alternative scenarios based on alternative water and wastewater systems and modifications to current systems which have been suggested by Sydney Water and the community in recent years. LCA analysis enables us to determine the environmental preferability of some of these alternatives and modifications based on the aspects of the system that have the greatest environmental effects.

Model construction

Functional unit

The functional unit is defined as the provision of water supply and sewerage services by Sydney Water in the year 2021. It is estimated that a total of 622 GL/a will be required at the customer areas (CAs). This figure and the sewage flows have been estimated based on the data from PlanningNSW regarding population density and the number of detached residential, multi-unit residential and commercial lots in each CA.

The *main* functions in this study are the supply of water, its distribution to the CAs, the treatment of wastewater and stormwater management in the year 2021. There are also supplementary functions within the system, i.e.

- *Nutrient recovery*: Treatment of biosolids and their application on land which potentially substitute the production of fertilizer.
- *Energy recovery*: Biogas production from anaerobic digestion and its utilisation for electricity generation. The generated electricity substitutes coal-based electricity production if the on-site generated energy is fed into the electricity grid.
- *Water recovery*: Treatment of wastewater to a sufficient standard for non-potable reuse will substitute the effort required to treat water to potable standard for the same use.

System boundaries

Sydney Water's strategic planning horizon is 20 years from the current date. Therefore the model base case process system was constructed to represent Sydney Water's current operating assets and future upgrades in accordance with available planning estimates and improvement policies. For example, this includes the upgrade of the quality of plants discharging to the ocean to full primary treatment and the servicing of outlying unsewered areas in accordance with the Sydney Water's Priority Sewage Program.

The system under study (see Figure 1) starts with the provision of water from the Sydney Catchment Authority (SCA). The water is pumped from 5 catchments to 9 water filtration plants (WFP) plants (5 operated by SWC and 4 under 'Build-Own-Operate' contracts (BOO). The water is pumped through water system areas to 55 customer areas (CA). Each customer area includes a certain number of single and multi-unit residences, and commercial and industrial lots. Water consumption is associated with residences and lots.

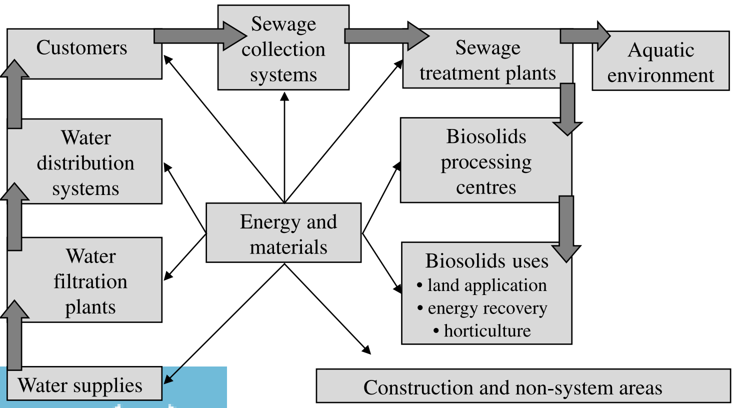

Figure 1 Schematic system boundaries for LCA

This data is based on Development Servicing Plans (DSP) used by PlanningNSW and other authorities. A large quantity of the water consumed in each customer area becomes wastewater which is pumped via wastewater system areas ("WWSA") to one or more sewage treatment plants (STPs). The 40 WWSAs do not map exactly onto the CAs nor WSAs. Sewage generated in each CA was apportioned to the appropriate WWSAs in accordance with flow data. Each WWSA connects to one of 41 STPs and the treated wastewater is reused for non-potable purposes or discharged to the marine or freshwater environment of Sydney. Biosolids are processed at one of seven biosolids processing centres. These are proposed regional centres located at STPs and catering for several plants. Biosolids products, whether dewatered, lime amended or dried, are sent to one of three biosolids end uses: horticultural composting facilities, land application or to power stations where biosolids can be a sustainable fuel replacing coal.

The LCA considered the non-system areas associated with environmental burdens (for example, office buildings and their consumption of electricity for lighting and climate control) and the infrastructure capital works commissioned by Sydney Water to maintain its level of service to customers. These were all what could be called the "foreground system" – the parts of the model which are directly part of Sydney Water's sphere of control. In addition, we included the suppliers of goods and services to Sydney Water so as to ensure that environmental impacts attributed to other organisations, but caused by Sydney Water's purchases, were included in the LCA. Each process component was modelled at the level of the individual sites performing a particular function.

Impact assessment model

It is the long-term aim to consider all direct and indirect environmental impacts that are caused by wastewater and its treatment. For all LCA applications in the wastewater industry the following impact categories are considered in order to reflect the specific Australian situation and particular issues relevant to wastewater treatment: total energy, water usage, climate change, freshwater and marine eutrophication, photochemical oxidant formation, human toxicity, aquatic freshwater and marine ecotoxicity, and terrestrial ecotoxicity.

These environmental indicators and impact categories reflect to varying degrees onsite and off-site impacts. These impact categories and indicators were chosen on the basis that they are most relevant to the wastewater industry.

Results of basecase assessment

By activity

The results of the base case LCA showed that, in decreasing order of frequency, most of the environmental burdens in the nine impact categories examined originate

- at sewage treatment plants (ocean STPs: 29% to total energy and climate change, 81% to freshwater and marine eutrophication, 24% to photochemical oxidant formation, 73% to human toxicity and 96% to marine ecotoxicity potential; inland STPs: 12% to total energy, 20% to climate change, 16% to freshwater and marine eutrophication, 19% to photochemical oxidant formation and 33% to aquatic freshwater ecotoxicity potential),
- within the biosolids management process (20% to human toxicity, 66% to aquatic freshwater ecotoxicity and 85% to terrestrial ecotoxicity),
- within the water reticulation system (28% to total energy and 24% to climate change),
- at water filtration plants (12% to total energy and 11% to climate change) or
- at customer areas (92% water usage).

The assessment of the base case therefore drew our attention to these activities in terms of examining the relative significance of the impacts in these nine categories and analysing potential actions to improved Sydney Water environmental performance. We examine improvements to these operations in the “scenario analyses” described below (detailed results are given in Lundie *et al.*, 2004).

By product consumption

Electricity consumption is very important as a mediator of Sydney Water’s regional and global impacts in all categories other than water consumption and terrestrial ecotoxicity. Nevertheless, it would be unwise to ignore the consumption of other materials, as the LCA demonstrated, even in terms of greenhouse gas emissions, 31% of Sydney Water’s total impact is mediated through the consumption of products other than electricity. So the electricity and other recurrently used materials are important products for consideration in improving Sydney Water environmental performance, while construction materials are relatively unimportant in the overall picture.

By comparing current systems

We also found it would be possible to use the base case data for internal benchmarking and examination of trade-offs between existing assets. For example, given that the Rouse Hill Water Recycling Facility consists of the additional microfiltration and ozonation unit operations attached to an STP designed for inland discharge, the LCA suggests that when less than 10% of the total plant’s electricity consumption is concerned with the additional unit operations, the delivery recycled water is positive by all envirommental measures. In fact, the additional unit operations consume approximately 15% of the plant’s electricity, so the LCA indicates the recycling at Rouse Hill would need to be justified in terms relating to water as a resource and its role in sustaining healthy river ecology, rather than energy and global warming potential, for example.

Scenario analyses

Results of scenario analyses are shown in Table 1. The values are normalised to the base case results, and cover the entire LCA system. The details of the modifications considered in each of the scenarios and the results are discussed below in turn.

Population changes and demand management

Sensitivity testing was performed to check the stability of the LCA results under varying population projections. We examined the impacts associated with an increase and decrease in the projected number of households served by Sydney Water in 2021 by 7 and 16%. The model responded as expected under these conditions, with the potential environmental impact category results changing by similar amounts, with some variation due to the variable degree to which they were controlled by fixed and variable material and energy consumption. This sensitivity testing showed that improvements in predicted environmental outcomes due to Sydney Water’s demand management activities were approximately equivalent to a reduction of Sydney’s population by 7% – equivalent to (the disappearance of) a regional city.

This figure does not include savings made by consumers. If Sydney Water’s subsidised low-flow shower roses were to be adopted by the entire customer base, the company would actually prevent the emission of more carbon dioxide than the amount for which it is currently responsible. Sydney Water estimates an average of approximately 1 T/a carbon dioxide is saved per household when demand management interventions are implemented. Under the basecase model, it is estimated that Sydney Water will serve 1.9

Table 1 Relative results of scenario analyses

	Total energy use [%]	**Water use [%]**	**Global warming potential [%]**	**Eutrophication potential [%]**	**Photchemical oxidant formation potential [%]**	**Human toxicity potential [%]**	**Freshwater aquatic ecotoxicity potential [%]**	**Marine aquatic ecotoxicity potential [%]**	**Terrestrial ecotoxicity potential [%]**
Basecase	100%	100%	100%	100%	100%	100%	100%	100%	100%
Demand Management	96%	94%	96%	94%	94%	94%	94%	94%	94%
Energy Efficiency	87%	100%	89%	99%	94%	99%	100%	100%	98%
Energy Generation	92%	100%	93%	100%	99%	100%	100%	100%	99%
Energy recovery from 50% biosolids combustion	96%	100%	98%	100%	98%	91%	71%	100%	61%
Desalination	127%	100%	123%	101%	105%	101%	100%	101%	103%
Secondary upgrades of major ocean STPs	123%	100%	121%	92%	116%	102%	102%	101%	151%
Secondary & tertiary upgrades of major ocean STPs	126%	100%	123%	90%	117%	102%	103%	101%	160%

million households in 2021. It is unrealistic to believe that all households will adopt such devices, but it is clear that the environmental benefits which can be gained by Sydney Water intervention in this area far exceed those obtainable by any modification to Sydney Water assets. Furthermore, it is estimated that approximately 0.7 T/a carbon dioxide is saved when a household upgrades its older dish and clothes-washing appliances to modern water-efficient models. As with the shower fittings, the key is the reduction in the use of hot water, and the energy savings made directly by the consumer, rather than any effects on Sydney Water's business or infrastructure. Comparison with the data produced by this LCA indicates that pursuing these savings by influencing regulators, offering rebates or by other means, should be a first priority among Sydney Water's activities to make Sydney more sustainable.

Energy efficiency and sustainable energy generation

Other scenario testing has shown the environmental value of internal energy efficiency measures and sustainable energy options. Energy efficiency targets suggested by preliminary estimates of the potential long-term savings possible for Sydney Water were adopted Table 2.

The improvements in energy efficiency result in nett improvements or no change across all impact categories. The biggest savings being in energy consumption (13%) and greenhouse gas emissions (11%). A 6% improvement in photochemical oxidant formation ("smog") potential is also obtained, which is mostly attributable to the projected 20,000 GJ/a (23%) improvement in the energy efficiency of Sydney Water's car fleet.

Though these environmental benefits would be obtained at some cost, most of the costs of pursuing these benefits could be seen as part of a maintenance and replacement program for less efficient Sydney Water pumping equipment, lighting fixtures, overpowered passenger vehicles and the like – when these relatively short-lived items "come up" for replacement. Significantly, there are no environmental reasons not to pursue these benefits.

The sustainable energy generation scenario incorporated the additional potential projects currently given some degree of consideration within Sydney Water (Some sustainable energy systems are included in the base case. This includes the current cogeneration facilities at Malabar and Cronulla, the hydroelectric system at the Illawarra WFP and the combustion of 10% of biosolids projected in the biosolids strategy). On the basis of available data, Warriewood STP was considered a sub-marginal cogeneration site due to its relative size and Liverpool STP was assumed to have insufficient quality energy available for cogeneration after installation of biosolids drying equipment in accordance with the

Table 2 Energy savings per system component

Sydney Water system component	Energy saving
Water delivery system	12%
Water filtration plants[1]	12%
Wastewater reticulation system	20%
Buildings	28%
Car fleet	20,000 GJ/a

[1] Water filtration plants are known to consume significant quantities of electricity for supply pumping, much as the water delivery system does. However, some plants use a high proportion of their electrical demand in the treatment process and little for pumping. We do not have any data on potential savings for the treatment process, so we conservatively assume that insignificant savings can be made in that activity. Of 9 WFPs, only Prospect and Orchard Hills have variable demand less than (mean-stdev) of the other plants. This quantity is also an order of magnitude lower than it is at the other plants on a volumetric basis. Thus, it was assumed that all WFPs other than Prospect and Orchard Hills achieve the overall efficiency savings shown

Biosolids Strategy. For the sustainable energy scenario it was assumed that an additional 40% of biosolids were used for energy recovery in Vales Point power station. Options included were therefore Table 3.

Implementation of all these energy generation options would result in significant improvements in all impact categories with the exception of water consumption. The Prospect mini-hydro plant is relatively significant in terms of its capacity to reduce Sydney Water's energy consumption and to prevent the need for unsustainably generated electricity to be produced. Using biosolids as a fuel to replace coal in thermal power stations has significant benefits both in terms of the replacement of a lithospheric carbon-based energy source with a renewable "solar biochemical" energy source, and the reduction in the quantity of biosolids being deposited on land. On the basis of the infinite timescale used in the LCA impact assessment models for terrestrial and freshwater ecotoxicity potentials, significant reductions in ecotoxicity are obtained, as a proportion of the low concentrations of heavy metals in the biosolids end up being removed from the ecosphere as solid waste from the combustion process. Additionally, the contribution which trucking biosolids makes to global warming and the toxic emissions in diesel exhaust are reduced by approximately 20%. This figure would be significantly higher if power stations are prepared to accept dewatered biosolids (34% solids content) rather than dried biosolids (92% solids content) as the mass of biosolids being trucked the relatively short distance to the power station. However, we conservatively assumed that all the biosolids delivered for energy recovery are dried.

Desalination for water supply

The environmental consequences of desalination are significant. As expected, the process demands significant additional resources Table 4.

In terms of the LCA impact assessment categories, desalination has no benefits. Since it does not reduce water consumption, but merely substitutes one form of supply for another, the only environmental benefits to be expressed are the retention of 5% of the water extracted from the Hawkesbury-Nepean River system in the base case. On the basis of energy consumption (the variable which in this case totally controls the global warming potential) the option of pumping water from the Shoalhaven River for 2.0 MWh/ML, is strongly favoured over desalination, which uses 4.5 MWh/ML. Other local environmental issues which LCA does not examine, for example, the particular flow requirements of the Shoalhaven River, have to be incorporated in Sydney Water's comparison of these options, but the LCA indicates that, if any additional demand management or supply alternatives to desalination exist, they deserve thorough investigation.

Table 3 Energy generation options

Energy generation option	Estimated output (MWh/a)
10 micro-hydro plants	2,200
Prospect mini-hydro plant	30,000
Woronora pipeline mini-hydro plant	2,100
Sugarloaf pipeline mini-hydro	4,500
Glenfield STP cogeneration	3,500
Wollongong STP cogeneration	3,600
North Head STP cogeneration	8,400
Combustion of additional biosolids	5,500
Total	59,800 (~210 TJ/a)

Table 4 Technical characteristics of desalination option

Desalination resource	Quantity used (saved)
Electricity	2,200 TJ/a
Calcium carbonate	1,200 T/a
Chlorine	70 T/a
Carbon dioxide	2,400 T/a
Raw water	(36.5 GL/a)

Upgrades for coastal STPs

In accordance with suggestions often made to Sydney Water by stakeholders and the community, this scenario examined the potential environmental effects of upgrading Sydney Water's three largest STPs: North Head, Bondi and Malabar. The analysis took the plants from the "full primary" level they are proposed to have attained by 2021 for the basecase model, to secondary and tertiary treatment levels.

Among the LCA impact categories examined, only eutrophication potential improved under the coastal STP upgrade scenario – performance in all other categories deteriorated. For an 8% improvement in the plants' contribution to eutrophication potential, the plants' energy demands increase by 25%, contributions to global warming rises by 21%, contributions to the potential for smog go up 22% and emissions with potential for terrestrial ecotoxicity rise 52%. The analysis shows that the main incremental environmental burdens associated with this upgrade are the consequence of the upgrade to secondary treatment, rather than the additional capital and recurrent impacts of a further upgrade to tertiary treatment. If tertiary treatment is sought, the corresponding values are 10% improvement and deteriorations of 28%, 23%, 23% and 60%. Clearly, for this choice to be environmentally preferable, a decision-maker would have to consider the risk of eutrophication or other marine pollution to outweigh all other environmental issues covered by the LCA. However, modelling of the local marine environment indicates that Sydney Water's eutrophication potential in the marine environment is insignificant compared to natural upwelling events (Pritchard *et al.*, 2001). This LCA indicates it is not worthwhile to put resources into upgrading the ocean plants unless additional environmental benefits can be generated, for example, by offsetting the demand for potable water through water recycling. However, seen in the context of the other scenarios, additional demand management initiatives would be more effective.

Greenfields urbanisation

A wide variety of different concepts and technologies could be examined under this scenario. Rather than examining a system which would be unlikely to be implemented due to cost or practical constraints, we compared delivery of traditional water and wastewater services with a local treatment and water efficiency option. This incorporated rainwater tanks for residential buildings, highly efficient (AAA-rated) household water appliances, and a combination of household primary (septic tank) sewage treatment with neighbourhood reticulated sandfilters and irrigation of treated effluent. Data from a Sydney Water/-CSIRO/UTS project examining designs for new urban areas was complemented with more detailed design and historical performance data published for the same type of system installed in the United States (Orenco, 2002). The system was scoped for a new urban area to house 12,000 people.

The results of the greenfields scenario are presented in Table 5. Since converting Sydney Water's services in established CAs to this greenfields alternative is technically infeasible due to the lack of irrigable land, these results are presented on the basis of the basecase for the new urban area. Consequently, much larger changes to the indicator

Table 5 Results of Greenfield scenario

	Total energy use	Water use	Global warming potential	Eutrophication potential	Photchemical oxidant formation	Human toxicity potential	Freshwater aquatic ecotoxicity	Marine aquatic ecotoxicity	Terrestrial ecotoxicity potential
Basecase	100%	100%	100%	100%	100%	100%	100%	100%	100%
Greenfields	83%	27%	82%	6%	37%	4%	13%	2%	33%

scores are achieved than in the other scenarios. In terms of the overall business, these changes would have to be scaled down by a factor of approximately 0.25% to reflect the impact they would have on the overall environmental performance of Sydney Water. Nevertheless, they indicate the potential to improve performance in greenfields sites around Sydney. Estimates of the contribution of greenfields sites to the increase in Sydney's population are highly variable and depend on a range of political factors, but Sydney Water currently expects about 20% of population growth to occur on the urban fringe.

The results indicate that the role of the material expenditure in the mediation of environmental impacts is relatively important for systems which involve significant construction activities at each household served. However, the overall environmental impacts are lower where such systems are feasible. One of the key reasons for this is the significant distance which potable water and raw sewage needs to be transported from the central processing facilities in order to deliver a conventional solution to the water and sewerage service needs of urban fringe suburbs.

Conclusions

In a new development for Sydney Water, we have been able to successfully apply LCA to the strategic planning process for the overall business. LCA is unique in its capacity to quantitatively compare options in terms of their ecological sustainability. It is important to capture environmental effects associated with the consumption of materials, which does not routinely occur in Sydney Water planning processes other than LCA. LCA provides a defensible methodological platform on which alternative future systems can be compared on a quantitative basis. It is not hampered by dollar-cost-mediation of environmental effects nor a limited view of Sydney Water as a business-scale system.

Valuable information regarding the energy and material demands of the water filtration process has been uncovered in the course of the inventorising demanded by the LCA methodology, which has not previously been incorporated in assessments of Sydney Water's environmental performance. This analysis has provided an improved methodology for calculation of Sydney Water's greenhouse gas emissions.

Life cycle assessment has been useful as an information tool for the examination of alternative future scenarios for WaterPlan 21. Sydney Water is now examining application of this methodology to other options selection processes.

Performing LCA has enabled Sydney Water to capture quantitatively environmental effects of the base case associated with the consumption of materials, which does not routinely occur in other strategic planning processes. Most of the scenarios are worthwhile pursuing from an environmental point of view. Most improvements are within Sydney Water's sphere of direct influence (energy efficiency and generation, energy recovery from 50% of biosolids scenarios), while customers have direct control of their water consumption (demand management). Improvements are largely *additive* if several scenarios are applied simultaneously.

References

Lundie, S., Peters, G. and Beavis, P. (2004). Life Cycle Assessment for Sustainable Metropolitan Water Systems Planning. In: *Environmental Science and Technology*. Online. April 2004.

Orenco (2002). Orenco Casestudy: Elkton, Oregon. Effluent sewer provides superior treatment at low cost. Accessed at www.orenco.com/PDFs/elktncs.pdf in April 2002.

Peters, G.M. and Lundie, S. (2002). Life-cycle assessment of biosolids processing options. *Journal of Industrial Ecology*, **5**(2), 103–121.

Pritchard, T., Lee, R., Ajanai, P., Rendell, P. and Black, K. (2001). How do ocean outfalls affect nurtient patterns in coastal waters of New South Wales, Australia? *Journal of Coastal Research, ICS 2001 Proceedings (special edition)*.

Tillman, A-M., Kärrman, E. and Nilsson, J. (1997). *Comparison of Environmental Impact Assessment, Life Cycle Assessment and Sustainable Development Records*. Report 1997:1, Technical Environmental Planning, Chalmers Tekniska Högskolan, Göteborg.