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Life Cycle Assessment (LCA) is useful as an information tool for the examination of alternative future scenarios for strategic planning. Developing a life cycle assessment for a large water and wastewater system involves making methodological decisions about the level of detail which is retained through different stages of the process. In this article we discuss a methodology tailored to strategic planning needs which retains a high degree of model segmentation in order to enhance modeling of a large, complex system. This is illustrated by a case study of Sydney Water, which is Australia's largest water service provider. A prospective LCA was carried out to examine the potential environmental impacts of Sydney Water's total operations in the year 2021. To our knowledge this is the first study to create an LCA model of an integrated water and wastewater system with this degree of complexity. A "base case" system model was constructed to represent current operating assets as augmented and upgraded to 2021. The base case results provided a basis for the comparison of alternative future scenarios and for conclusions to be drawn regarding potential environmental improvements. The scenarios can be roughly classified in two categories: (1) options which improve the environmental performance across all impact categories and (2) options which improve one indicator and worsen others. Overall environmental improvements are achieved in all categories by the scenarios examining increased demand management, energy efficiency, energy generation, and additional energy recovery from biosolids. The scenarios which examined desalination of seawater and the upgrades of major coastal sewage treatment plants to secondary and tertiary treatment produced an improvement in one environmental indicator but deteriorations in all the other impact categories, indicating the environmental tradeoffs within the system. The desalination scenario produced a significant increase in greenhouse gas emissions due to coal-fired electricity generation for a small increase in water supply. Assessment of a greenfield scenario incorporating water demand management, on-site treatment, local irrigation, and centralized biosolids treatment indicates significant environmental improvements are possible relative to the assessment of a conventional system of corresponding scale.

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Introduction

Previous LCA studies in the area of water cycle management have mainly addressed specific aspects of wastewater systems, i.e., quantifying environmental loads of wastewater systems (*1*−*5*) or biosolids systems (*6*, *7*). Fewer LCA studies of water supply alternatives (*8*, *9*) have been published. LCA has also been used for the definition of environmental sustainability indicators for wastewater systems (*10*, *11*) and more recently for urban water systems (*12*).

Recent Swedish studies have incorporated some of the most comprehensive LCA system boundaries, including water, sewage, and sludge treatment and avoided fertilizer production (e.g., refs *2* and *4*) as have been discussed in greater detail previously (*1*). These studies developed detailed inventories at the unit operations level for essentially one wastewater facility per case study. In some cases (*2*, *4*), biosolids treatment is performed at a facility separate from the liquids treatment facility. In terms of the multiplicity of linked facilities, a study of Thames Water (*7*) may be the most complex wastewater LCA published to date, involving different treatment options and transport connections between 15 sewage treatment plants, but as the study was concerned with biosolids options, the system boundary was not as broad as the Swedish work, and water supply systems were not included. This article describes research which used the same comprehensive approach to system boundary definition as the Swedish studies and with a larger, more complex set of facilities than the Thames Water study. To our knowledge, this is the first time an overall LCA perspective of a water and sewerage system of this megalopolitan scale has been published.

Whether publicly or privately operated, water and wastewater systems are often directed by government organizations which need to demonstrate that their performance and their planning processes meet the public's expectations in terms of ecologically sustainable development (ESD). This concern with sustainability creates a role for LCA. Sydney Water, for example, is required to conduct its operations in accordance with the principles of ESD by state law (*13*). This requires "...effective integration of economic and environmental considerations in decision-making processes" (*14*). WaterPlan 21 is Sydney Water's long-term strategic vision and is intended to guide infrastructure planning toward ESD. WaterPlan 21 was reviewed in 2001−2002 to bring it up-to-date with developments in the organization and its operating environment. The review required some kind of technical environmental planning tool to compliment the economic and financial tools.

LCA was chosen to examine the potential environmental impacts of Sydney Water's operations in the year 2021. LCA is seen as a tool more holistic, quantitative, comparative, and predictive than the few alternatives available for comparing alternative technical systems. Additionally, LCA had already been successfully applied to strategic environmental assessment of alternative biosolids treatment options in Sydney (*6*). LCA seemed to be the most appropriate tool

TABLE 1. Processes with Direct and Indirect Impacts Associated with Environmental Categories

environmental indicators and impact categories	direct: on-site (includes all processes that are required for on-site wastewater treatment)	direct: off-site (includes all processes that are required for off-site treatment of byproducts)	indirect (includes all off-site processes that are required for facilitating wastewater treatment)
total energy	energy recovery	transportation biosolids application water reuse/recycling	electricity supply[a] chemical production[a]
climate change	gaseous emissions from sewerage and STPs	gaseous emissions	electricity supply[a] chemical production[a]
freshwater and marine eutrophication	treated effluent discharge	transportation biosolids application water reuse/recycling	electricity supply[a] chemical production[a]
photochemical oxidant formation	CO from biogas flaring; NMVOC from denitrification	transportation biosolids application water reuse/recycling	electricity supply[a] chemical production[a]
human toxicity	gaseous emissions from sewerage and STPs treated effluent discharge	transportation biosolids application water reuse/recycling	electricity supply[a] chemical production[a]
aquatic ecotoxicity	gaseous emissions from sewerage and STPs treated effluent discharge	transportation biosolids application water reuse/recycling	electricity supply[a] chemical production[a]
terrestrial ecotoxicity	gaseous emissions from sewerage and STPs treated effluent discharge	transportation biosolids application water reuse/recycling	electricity supply[a] chemical production[a]

[a] Some of these environmental impacts may be mediated by multiple steps, e.g., precipitation of gaseous emissions of power plants into the air with ultimate impacts on the aquatic environment.

to identify and quantitatively assess possible environmental problem shifting that could be caused by planning decisions. The aim of this study is to compare the relative sustainability of operations under different planning scenarios, enabling consideration of environmental issues in parallel with financial, social, and practical considerations in strategic planning.

Methodology

In this section we describe a methodology for performing prospective (future-orientated) LCAs that is consistent with the ISO 14040 framework (*15*−*18*) and relevant to large urban water organizations or other service companies operating complex infrastructure networks. The main purpose of water service companies is the provision of water supply and sewerage services to residential, industrial, and commercial customers. On this account it is sensible to choose a functional unit that is related to the annual water flow throughout the system, i.e., delivery of a volume of potable water or management of a volume of wastewater. The use of this type of functional unit enables alternative technical system models to be compared consistently. For example, where scenarios consider water-efficiency initiatives, appropriate adjustment of the scale of the functional unit can be made. Water systems supply additional functions including the following: (1) *nutrient recovery* − the treatment and land application of biosolids brings back the nutrients to the natural cycle in agriculture, horticulture, and forest systems, which can prevent the need for chemical fertilizers and thus avoid their production; (2) *energy recovery* − which can include the generation of electricity or the cogeneration of thermal energy and electricity from biogas at sewage treatment plants (STPs) or biosolids combustion off-site [This generation activity replaces the production of electrical and thermal energy from other energy sources.]; and (3) *water reuse* − treatment of wastewater to a quality sufficient for reuse can substitute for the engineering effort required to supply potable water to fulfill the same needs.

To assess water supply and sewerage services in a holistic manner, all changes in environmental performance of the main as well as the supplementary functions have to be considered. In general, impact categories are chosen to examine the issues which are considered relevant to the current business impacts of the service provider and the changes in environmental performance which new scenarios may cause. Typical categories of relevance to the water industry include the following: total energy use, water use, contributions to climate change (this category is based on greenhouse gas emissions and is also called "global warming potential"), eutrophication potential (EP), photochemical oxidant formation potential (POFP), human toxicity potential (HTP), freshwater and marine aquatic ecotoxicity potential (FAETP and MAETP), and terrestrial ecotoxicity potential (TETP). Odor impacts from sewage pipelines and sewage treatment processes may become a problem if a certain concentration of odorous substances is exceeded. However, this issue has been excluded from all the water LCAs of which we are aware. Due to a lack of appropriate data, this impact category has been excluded from this analysis. These environmental indicators and impact categories reflect on-site and off-site impacts to varying degrees (see Table 1). A detailed description of these indicators and impact categories can be found elsewhere (*19*, *20*).

To address the environmental issues and to allow sufficient flexibility to permit the assessment of a wide variety of alternative scenarios, a model simulating the current potable water and wastewater flow from the bulk water supplies (BWS) to water filtration plants (WFPs), water system areas (WSAs), customer areas (CAs), wastewater system areas (WWSAs), and sewage treatment plants (STPs) is constructed (see Figure 1).

Each of these areas and plants is separately modeled using details of the performance of each individual unit with its own mass and energy balance. The demand for chemicals and energy, and the production of grit, screenings, biosolds, and biogas are estimated on a per kiloliter (kL) basis. The

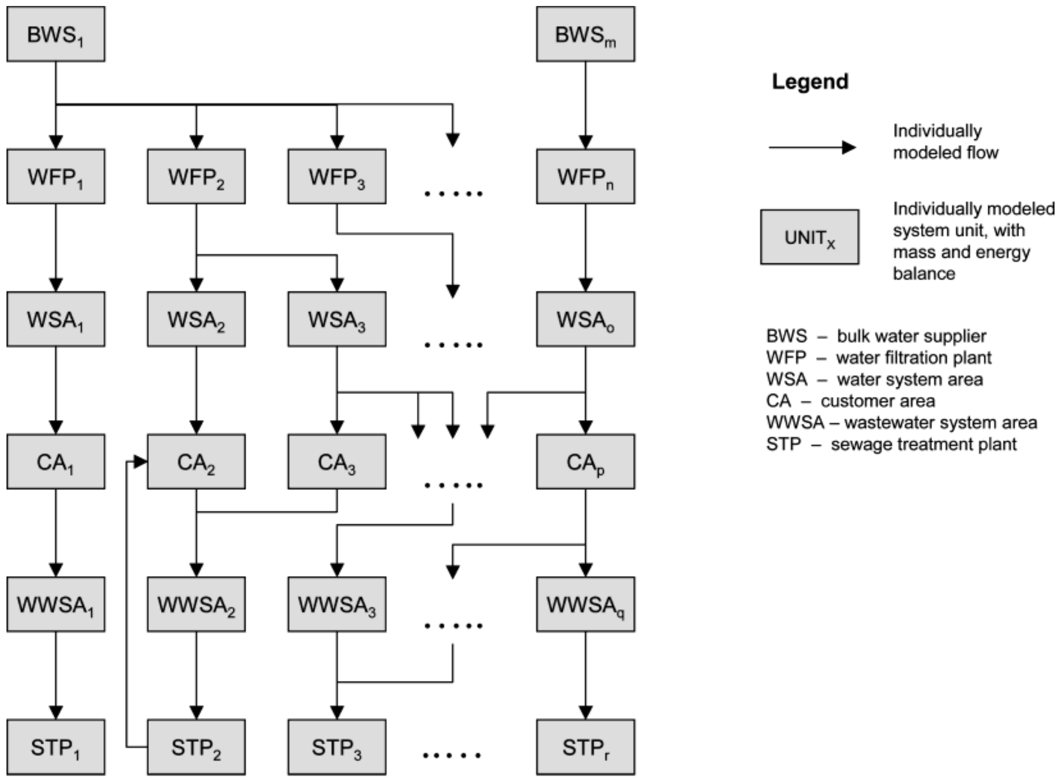

FIGURE 1. Schematic diagram of the LCA model.

water demand is calculated for each CA on the basis of the number of single and multiunit residences and commercial and industrial lots in each area and data on the typical water consumption and sewage generation of each type of lot. Additionally, the LCA model should include the environmental burdens of so-called “nonsystem areas”, such as office buildings and vehicle fleets. Nonconsumable materials are included by way of estimates of the additional materials that will be required in the future to cope with system upgrades and maintenance. Impacts of the production of the construction materials are included, but energy used during the construction process is excluded. This is a simplification based on other wastewater case studies (*4*, *12*) which have concluded that operational impacts are more important than asset creation impacts and that material production is the most important part of the asset creation impacts.

Life Cycle Inventory (LCI) data are extrapolated from current annual performance data to the reference year in the future. After validation of specific mass and energy balances per kiloliter (kL), the LCI data are related to the functional unit in the software model. Historical energy data are analyzed for each WSA and WWSA, and a calculation is made to apportion fixed and variable energy consumption for each process unit in each area. Statistical analysis of historical performance data is performed to determine the fixed and variable (flow dependent) energy demands for each of these process units in each area.

Application of Methodology to Sydney Water

For the review of Waterplan 21, a life cycle perspective was chosen to allow a holistic assessment of the environmental impacts of Sydney Water’s combined operations. The LCA was intended to show which aspects of the business place the largest burdens on the environment and to compare alternative future scenarios. By allowing this holistic perspective of environmental issues, the LCA offers a means to move beyond “end-of-pipe” thinking in understanding the sustainability of water service provision.

The investigation was based on a functional unit defined as the provision of water supply and sewerage services in the year 2021. This was estimated to mean the provision of 622 GL of water per annum to residential, industrial, and commercial customers. In accordance with the findings of similar LCA studies concerned with single STPs, such as ref *1*, the boundaries of the LCA system were expanded to include the producers of electricity, chemicals and fertilizers (the latter was considered to be among the system’s “material suppliers” as shown in Figure 2).

The base case process system model was constructed to represent Sydney Water’s current operating assets as augmented and upgraded to 2021 in accordance with planning estimates and improvement policies. To simplify database management and process visualization, the LCA software GaBi (*21*) was selected.

For the same reason, the water and sewerage systems were modeled in a large number of subareas based on the geographical pattern of reticulation actually present in Sydney. Water delivery systems and sewage catchments do not share common boundaries, and Sydney’s hilly topography has fostered a complex arrangement of sewage subcatchments, fragmented by gravitational flow considerations. As a consequence, the LCA model was more complex than any other water and wastewater LCA in the literature. Figure 1 indicates the level of detail included in the LCA model, starting with two BWSs being the Sydney Catchment Authority and the Hawkesbury River at Richmond, New South Wales. Water is distributed to 9 WFPs and is pumped through 13 WSAs to 55 CAs. The 40 WWSAs are sometimes fed by multiple CAs, for example, the North Head WWSA serves at least a portion of 18 CAs. Each WWSA connects to one of 31 STPs, and the treated wastewater is reused for nonpotable purposes or discharged to marine or freshwater environments. Doing the modeling at this level of detail enabled us to examine a number of alternative scenarios with greater ease than would be the case if a simpler segmentation with larger model components were used.

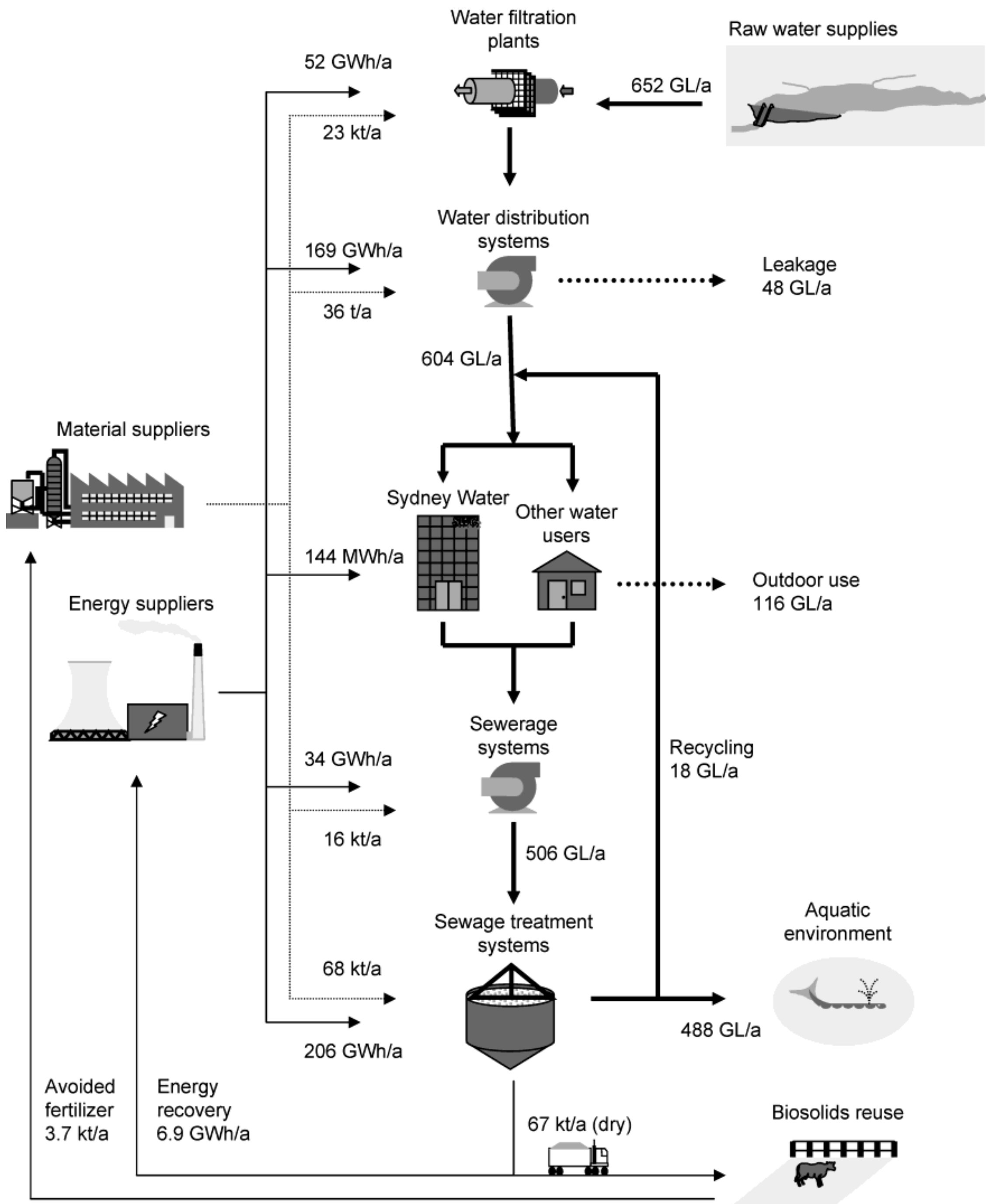

FIGURE 2. Simplified flow diagram within the defined system boundaries for the Sydney Water system.

Biosolids are processed at one of seven biosolids processing centers in the LCA model. Some of these regional centers are already in operation, others are proposed. Dewatered biosolids products, which are in some cases also lime-amended or dried, are sent to one of three biosolids end uses: direct land application, horticultural composting, or combustion as fuel in electrical power stations as an alternative to coal (see Figure 2).

Previous LCA studies (*1*−*4*, *6*−*12*), Australian LCI data (*22*), and company data were used where necessary to generate reliable LCI data on materials, chemicals, energy, and transportation. Most of the electricity generated in NSW (91%) comes from coal-fired powerstations (*23*). Hydroelectricity (from the Snowy Mountains Hydroelectric Scheme and other small hydro power stations) represents only 6% of electrical generation in New South Wales. The remainder comes from gas (natural gas, coal seam methane, and landfill gas), bagasse, solar power, and wind generators.

The site-specificity of the data collected for the base case ensured a generally high degree of confidence in the inventory results. Emission inventories for energy recovery from biosolids have only a lower degree of confidence (see Table 2).

The LCI data were then characterized using several impact models. Most impact categories were based on international best practice (*19*, *20*), while recent improvements in the eutrophication potential category (*29*) were adopted and adapted to the specific circumstances in greater Sydney region (*30*), where it is unclear whether freshwater streams are generally nitrogen or phosphorus limited. Australian impact assessment models were applied for human toxicity and ecotoxicity potentials (*31*, *32*).

TABLE 2. Characterization of Life Cycle Inventory Data

	life cycle component		basis of the data	data quality	comment on basis for inventory formation
STPs	effluent composition		site specific measurements	high	current performance data extrapolated for each individual STP
	emissions	nitrogenous	generic estimate	medium	nitrous oxide, NMVOC emissions estimated for biological denitrification plants (*24–26*)
		biogas	site specific measurements and estimates	high	measured performance data for major STPs, estimates for smaller plants
energy consumption			site specific measurements	high	identification of fixed and variable (pumping) components for each unit and area in the SWC system
chemical production	chlorine products		manufacturer's data	high	producer-specific data based using cell membrane process
	other		calculated	medium	international data modified for Australian conditions
biosolids	composition		site specific measurements	high	inventories based on yearly returns for each STP sampled every 100 dry tonnes
	avoided fertilizer		estimated	medium	inventories constructed based on known technology and N (*27*) and P (*2*) equivalence
	avoided energy recovery		estimated	medium	emissions based on fluidized bed technology (*28*)
construction			estimated	medium	materials quantities calculated from actual engineering drawings of equivalent unit processes
logistics			site specific data	high	data obtained from logistics managers
nonsystem areas			site specific data	high	data obtained from facilities managers

Base Case — LCA Results

LCI analysis was used to calculate the total material and energy flows for the entire system. Over 42% of Sydney Water's material demand consists of ferrous chloride, which is used for the removal of phosphorus at STPs and the control of odorous sulfur compounds in WWSAs. Ferric chloride is also required in large quantities at STPs and WFPs and makes 13% of the total material demand. Large quantities of grit, screenings, biosolids, and water filtration residuals are removed by Sydney Water. Grit and screenings from STPs (13 700 wt/a) are sent to landfills, while water filtration residuals are used for landscaping purposes. Biosolids (129 200 wt/a) are beneficially applied at farms (76%), for composting purposes (14%) or for energy recovery (10%) in the LCA model. The production of 433 t/a of nitrogen fertilizer and 3250 t/a of phosphorus fertilizer (superphosphate) are avoided by the beneficial reuse of biosolids. The proposed recovery of energy from 10% of Sydney Water's biosolids is estimated to generate 24.7 TJ/a of electricity. Approximately 81% of all transportation effort (in tonne-kilometer terms) is consequent to the transportation of biosolids to farms. This is due to the long average distance (309 km) from the biosolids processing centers to farm application and transportation of the large mass of water which remains in "dewatered" biosolids. Approximately 9600 t/a of biogas is generated at Sydney Water's STPs. Forty-three percent is used for electricity production, while 52% is flared. Five percent of the biogas is released to the atmosphere without further treatment.

Table 3 shows the total contributions of Sydney Water to each environmental indicator and impact category and the relative contribution of each activity to the total system contributions for the base case. Of Sydney Water's installations, the coastal STPs emit the most nutrients and are responsible for the largest proportions of most indicator categories. However, the nutrients are emitted to a relatively insensitive environment. A marine pycnocline (density stratification) limits the ability of the nutrients to rise to levels at which photosynthesis could occur (*33*). Correlations have been shown between local eutrophication effects off Sydney's shoreline and the occurrence of El Niño events (*34*), suggesting that although humankind may have increased the likelihood of algal blooms by its intervention in the carbon cycle, the direct influence of 81% of Sydney Water's eutrophication potential seems to be relatively unimportant in this respect. Inland STPs make a large contribution to FAETP relative to the rest of the Sydney Water system, while their contributions to the other categories are smaller. WSAs are associated with a major part of Sydney Water's total energy usage and contributions to climate change—solely due to their electricity consumption. WFPs have similar but smaller category indicator results in the total energy usage and climate change categories. The biosolids system achieves environmental savings in the impact categories of total energy, water usage, and climate change due to the beneficial application of biosolids on farms, for composting and for energy recovery purposes. There are emissions from the biosolids system relevant to HTP, FAETP, and TETP predominantly due to the application of biosolids to land. The remaining system components such as water recycling, infrastructure, nonsystem areas, grit, and screenings are of lesser importance.

Scenario Analysis

Several scenarios were investigated in order to compare the environmental performance of alternative systems. Most of the scenarios listed in Table 4 may be considered "what if" scenarios (*35*) where quantitative comparisons are modeled using operational information. The greenfield scenario may be considered a "cornerstone" scenario where less certain information was applied to permit scenario planning of decentralized systems. The combination of "what if" and "cornerstone" scenarios allows the utility to explore and

TABLE 3. LCIA Results of the Base Case

environmental indicators/ impact categories	resource use: total energy use	resource use: water use	output-related categories: climate change	eutrophication potential	photochemical oxidant formation potential	human toxicity potential	freshwater aquatic ecotoxicity potential	marine aquatic ecotoxicity potential	terrestrial ecotoxicity potential
	TJ/a	GL/a	kt CO_2/a	kt O_2/a	t ethene/a	kt DCB/a	kt DCB/a	kt DCB/a	kt DCB/a
total	8110	655	721	231	127	63.1	75.6	506000	42.5
Percentage Contributions Relative to Sydney Water's Total for Each Impact Category									
water filtration plants	12%	<1%	11%	1%	9%	1%	<1%	1%	2%
water system areas	28%	8%	24%	1%	5%	1%	<1%	1%	4%
customer areas		92%							
wastewater system areas	8%		7%	<1%	11%	<1%	-	<1%	1%
inland STPs	12%	<1%	20%	16%	19%	5%	33%	2%	2%
coastal STPs	29%	<1%	29%	81%	24%	73%	<1%	96%	5%
water recycling by STPs	1%		1%		<1%	<1%			<1%
recycled water distribution	1%		1%		<1%				<1%
biosolids system	−1%	<−1%	−1%	1%	7%	20%	66%	<1%	85%
infrastructure	4%		4%	<1%	2%				<1%
nonsystem areas	6%		5%	<1%	23%	<1%		<1%	1%
total	100%	100%	100%	100%	100%	100%	100%	100%	100%

TABLE 4. Scenarios Assessed in this Study

scenario	description
desalination	construction and continuous operation of a seawater desalination plant to provide 6% of Sydney Water's supplies
demand management	implement additional demand management initiatives to reduce demand by a further 6%
population changes	assess the influence of four alternative population estimates for Sydney (±7%; ±16%)
energy efficiency	install high efficiency pumps in all water and sewage infrastructure; reduce car sizes; improve the efficiency of lighting
energy generation	increase electricity generation using opportunities for hydroelectricity and biogas combustion
energy from biosolids	co-combustion of half of Sydney Water's captured biosolids in power stations
upgrade coastal STPs	implementation of (a) secondary and (b) secondary and tertiary treatment upgrades to Sydney water's 3 major STPs discharging treated wastewater via deep ocean outfalls
greenfield	implement integrated local water cycle management concepts in a new suburb: water efficient appliances; rainwater tanks; on-site primary treatment with neighborhood-scale nutrient removal facilities; local recycling of treated wastewater for irrigation and regional biosolids treatment

prioritise initiatives to mitigate future environmental impacts. The results of the scenario analyses are summarized in Table 5.

Pursuit of the *desalination scenario* would cause noticeable deteriorations in the sustainability indicators examined in this work and offset only 6% of the annual water demand. The effects include an increase in all impact categories except water use due to application of the energy-intense reverse osmosis process in a modern desalination facility. Although it was modeled as a small component of one part of Sydney Water's business, desalination of seawater for permanent supply of potable water causes a significant deterioration in the environmental performance of the overall business. On the basis of the base case results, we may calculate that if Sydney's demand for water was fully supplied by desalination plants with the same process technology, the energy consumption of the entire system would increase by a factor of 6 and its contribution to climate change would increase 5-fold.

The *population scenarios* confirm that the environmental system performance is sensitive to the actual population growth. The potential environmental impact category results vary in proportion to the change in population, although the relationship is not one-to-one since some components of the material flows are fixed. These scenarios show that improvements in predicted environmental outcomes due to demand management activities are approximately equivalent to a reduction in Sydney's predicted population growth by 7%. This underlines the importance of accurate population figures for environmental planning at Sydney Water.

In the *demand management scenario* a reduced water demand of 6% was predicted, which resulted in savings of approximately the same scale across all impact categories since less energy and chemicals were required for the treatment of freshwater and wastewater.

The initiatives considered in the *energy efficiency scenario* result in net improvements or no change across all impact categories. The biggest savings are in energy consumption (13%) and greenhouse gas emissions. A reduction in POFP is also obtained, mostly attributable to the projected 20 000 GJ/a 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 passenger vehicles, less efficient pumping equipment, lighting fixtures and the like—when these relatively short-lived items are due for replacement. There are no environmental reasons not to pursue these benefits.

Implementation of the *renewable energy generation scenario* would result in savings similar to the energy efficiency scenario. The biggest single item, a possible

TABLE 5. Comparison of Scenarios against the Base Case for Each Environmental Indicator and Impact Category

	total energy (%)	water usage (%)	climate change (%)	eutrophication potential (%)	photochemical oxidant formation potential (%)	human toxicity potential (%)	freshwater aquatic ecotoxicity potential (%)	marine aquatic ecotoxicity potential (%)	terrestrial ecotoxicity potential (%)
desalination	27	0	23	1	5	1	0	1	3
demand management	−4	−6	−4	−6	−6	−6	−6	−6	−6
energy efficiency	−13	0	−11	−1	−6	−1	0	0	−2
energy generation	−8	0	−7	0	−1	0	0	0	−1
energy recovery from 50% biosolids	−4	0	−2	0	−2	−9	−29	0	−39
population +7%	3	7	4	7	6	7	7	7	7
population +16%	8	16	10	16	15	16	16	16	15
population −7%	−4	−6	−5	−6	−6	−6	−6	−6	−6
population −16%	−8	−12	−8	−12	−11	−12	−12	−12	−11
secondary upgrade of major coastal STPs	23	0	21	−8	16	2	2	0	51
secondary & tertiary upgrade of major coastal STPs	26	0	23	−10	17	2	3	0	60

hydroelectric facility to use the pressure head on the supply pipeline from Sydney's largest dam, is estimated to provide half of these benefits.

Using biosolids as a fuel to replace coal in thermal power stations (*energy recovery from 50% biosolids scenario*) would have 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 time scale used in the LCA impact assessment models for terrestrial and freshwater ecotoxicity impact categories, significant reductions in ecotoxicity potentials are obtained. This is because a proportion of the trace concentrations of heavy metals in the biosolids which would otherwise be applied to land is redirected out of the environment and into confined landfills when ash from combustion is sent to disposal. Additionally, the contribution which the transportation of biosolids would make to climate change and the potentially toxic emissions in diesel exhaust is reduced by approximately 20%. However, more rigorous emission inventories for energy recovery from biosolids under different technologies need to be developed to provide confidence that environmental problem shifting (from terrestrial to atmospheric emissions) is not occurring. LCI data is based on literature (*28, 36*) rather than measured data.

The *upgrade of major coastal treatment plants* to secondary and tertiary treatment improves the effluent quality of 63% of the volume of treated wastewater discharged to the environment by Sydney Water. By upgrading to secondary or tertiary treatment, a large reduction in EP is achieved, i.e., 22 500 tO_2/a (reduction by 8%) or 27 400 tO_2/a (reduction by 10%), respectively. However, Sydney Water's energy demands and contributions to climate change increase by over 20% (more than twice the scale of the improvement in EP). Contributions to the potential for smog go up by 16%, and the TETP rises by more than 50% of its base case value. The tertiary treatment scenario is similar, showing slightly larger deviations from base case values in each category, indicating that the step from primary to secondary treatment is more significant than the step from secondary to tertiary. Total energy and greenhouse gas emissions go up as a consequence of higher energy and chemical consumption at STPs, while the increase in POFP and TETP can be attributed to the additional biosolids transportation and application at land. The quantity of biosolids increases by 71% for secondary treatment and by 83% for secondary and tertiary treatment relative to the base case. This represents 6150 and 7140 additional truck movements per year, respectively. On the basis of this LCA it would not be worthwhile to put resources into upgrading the coastal plants unless eutrophication or other environmental impacts are perceived as significant, or additional environmental benefits can be generated by offsetting the demand for potable water through water recycling.

Analysis of the *greenfield scenario* revealed environmental benefits in all indicator categories on a per household basis. Most significant is the reduction of freshwater usage by 73% relative to the base case. Total energy usage and greenhouse gas emissions are reduced by 17% and 18%, respectively. EP is reduced by a factor of approximately 10 due to the removal of nutrients in the recirculating sand filter and the use of treated wastewater for irrigation. HTP, FAETP, and MAETP are reduced to 4%, 13%, and 2% of the base case results, respectively. These improvements are primarily due to the diversion of partially treated wastewater from the aquatic environment to irrigative land application. The POFP result for this scenario was reduced by 63% compared with the base case due to the avoidance of some wastewater treatment chemicals and the consequent avoided production of carbon monoxide during their manufacturing processes. For the nontoxicity indicators, construction of infrastructure represents a high proportion (40−50%) of the indicator impacts. The fabrication of rainwater tanks with steel is the dominant contributor to this. This contribution would be reduced by a factor of 10 if the steel tank was replaced with an equivalent concrete tank (see ref *37* for further greenfield options).

For simplicity, the greenfields scenario performance is compared with traditional water and wastewater service delivery for the same number of residents. The environmental improvements obtained by implementation of greenfields solutions in all new urban areas are less pronounced if the improvements are examined on the basis of the performance of the entire system (including all the old housing, commercial and industrial customers). Assessment of the *greenfield scenario* with water demand management, on-site wastewater treatment with local irrigation, and centralized biosolids treatment indicates significant environmental improvements are possible relative to the assessment of a conventional system of corresponding scale.

Discussion of Results

LCA methodology has been applied successfully to the strategic planning process for the overall business of Sydney Water. LCA provides a defensible methodological platform on which to quantify environmental burdens associated with the base case and on which alternative future systems can be compared on a quantitative basis. LCA allows environmental benchmarking of "business as usual" against promising alternatives for sustainable water services. Using LCA early on in the planning process helps ensure that environmental issues are considered. Although not its first LCA, performing an LCA on this scale has been a new undertaking for Sydney Water. Building a model of the scale and complexity as this one can be a resource-intensive process, but the discipline has benefits beyond the performance of the LCA itself and the insights which it gives to strategic planners. The process of constructing the LCI involves information exchanges between planning and operational staff which can enhance communication in a large organization. It has also provided information which has enriched communication with external stakeholders. Performing LCA has enabled Sydney Water to capture environmental effects associated with the consumption of materials, which does not routinely occur in other strategic planning processes. Having developed its understanding of LCA and its application to water and wastewater infrastructure, Sydney Water is considering how it might apply the methodology to future planning questions.

In the LCA model, reusing biosolids avoids the production of nitrogenous and superphosphate fertilizer as well as coal-fired electricity. Keeping nutrients in the agricultural production cycle rather than discharging them to aquatic ecosystems has a beneficial influence on the results. The reduction in environmental burdens due to biosolids application on farmland is significantly reduced or undone by the transport distances from the biosolids center to the application.

Effluent quality is a major component of Sydney Water's calculated LCA output-oriented indicators. These potential environmental burdens are predominantly due to treatment levels at the coastal STPs. The STPs manage the majority of Sydney's sewage and treat it to New South Wales Environmental Protection Authority standards which are concerned with preventing prioritized environmental impacts rather than minimizing overall environmental burdens.

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, the consumption of other materials, such as chemicals, should not be ignored. Process chemicals make a large contribution to total energy and climate change indicators (12% of each) and 49% of POFP. Taken together, these results indicate the significance of Sydney Water's suppliers in mediating the overall environmental burdens of the business.

The proportions of the environmental indicator scores which result from the construction of infrastructure are small, i.e., 4% or less of each impact category. Hence, it can be concluded that the operational phase is much more significant than the impacts from capital equipment. This result is consistent with the conclusions of other "what if" studies of centralized systems (e.g., ref *38*).

Nonsystem areas (petrol and diesel vehicle fleet and office buildings) make a significant contribution to photochemical oxidant formation and to a lesser extent to total energy and greenhouse gas emissions. Therefore it is important to include them in environmental assessments of businesses such as Sydney Water, despite the fact that their operation is not usually the focus of such environmental assessments.

In this LCA, we have not attempted to produce a single indicator of environmental impact, preferring to avoid applying societal or other weighting procedures which are sometimes used to aggregate several indicator scores. While this means it takes more effort to understand the results, the disaggregated information is more amenable to inclusion in other decision making processes and is intrinsically simpler and more robust. Consequently, a clear rank order of alternatives cannot be generated. 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. Consequently, an overall improvement in the indicator scores of between 10 and 30% would be expected if they are all implemented in the LCA model.

This detailed approach to LCA allows quantitative comparisons of alternative future systems to be made. Construction of this detailed LCA model will allow Sydney Water maximum flexibility to revisit the model in the future and compare other scenarios which may become significant planning options. Life cycle assessment has been useful as an information tool for the examination of alternative future scenarios for WaterPlan 21. The LCA model allows alterations in population growth, demand management, and treatment quality assumptions to be rapidly assessed.

The cradle to grave approach is a useful compliment to assessment of financial, social, and local environmental issues, which are all necessary when making decisions about the future of Sydney Water's operations. Like a number of other organizations, Sydney Water procures parts of its operations through Build-Own-Operate arrangements with private consortia. LCA includes the environmental significance of such operations in its overall calculations and shows the importance of considering both the upstream and downstream supply chains during the strategic planning process. This LCA has demonstrated the significance of understanding supply chains as part of assessing the environmental effects of a water and wastewater business. Choosing suppliers of goods and services with better environmental performance is important to such a business. LCA can help to "green the supply chain" by providing a methodological framework for assessing inputs, such as energy and chemicals and comparing those inputs with alternatives.

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Note Added after ASAP Posting

This paper was released ASAP on 05/21/2004 with an incorrect unit at the bottom of Figure 2. The correct version was posted on 06/02/2004.

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