

LIFE CYCLE IMPACTS OF THE GOLD COAST URBAN WATER CYCLE

Joe Lane¹, David de Haas^{1,2}, Paul Lant¹

1. University of Queensland, Brisbane, QLD

2. GHD, Brisbane, QLD

ABSTRACT

Quantitative life-cycle assessment (LCA) was used to consider the environmental burdens associated with the urban water cycle of the Gold Coast, Queensland, Australia. Detailed inventories were collected for all the major infrastructure types involved, in order to assess performance across a range of environmental and resource-use impacts. An analysis of the existing water cycle infrastructure shows that it is the wastewater management (collection, treatment and disposal) step that makes the biggest contribution to most of the environmental impacts. Across the whole water cycle, chemicals use should be included with electricity use and fugitive gas emissions as the biggest concerns from a greenhouse gas risk mitigation perspective. The results suggest that the ecotoxicological implications of agricultural biosolids reuse, and of marine effluent discharge, warrant further consideration. The irrigation disposal pathway made a lesser contribution to the toxicity results, and the contribution of metals far outweighed that of organic micropollutants in all water cycle flows. Both rainwater tanks and Class A+ recycling showed increased overall impacts (Global Warming Potential, Fossil Fuel Extraction, Toxicity) compared with the low energy dam supplies that are the norm. Reduced freshwater extraction is the key benefit from recycling and rainwater tanks, although the Class A+ model did not deliver any substantial benefits beyond those available from a rainwater tank. This finding is dependent on the low household water demand profile used, and might be different under other circumstances. The relevance of key data uncertainties is noted. In particular, fugitive greenhouse gas emissions, rainwater tank energy burdens, and the implications of nutrient land application, should be considered carefully in the water cycle planning process.

INTRODUCTION

The South East Queensland (SEQ) urban water cycle has been in a significant state of flux for the past decade. Public demand for improved protection of local waterways has driven large reductions in nutrient discharge to the aquatic environment. Recent local drought resulted in severe short term water shortages, while a rapidly growing population has brought on longer term

planning for alternative water supply sources that can supplement the traditional dam supplies (QWC 2009). A small number of schemes based on high levels of wastewater recycling have been implemented (to varying degrees) in a somewhat piecemeal fashion across the region. Recent shifts in public concern and policy related to greenhouse gas emissions has led to an increased focus on energy use in the urban water sector (QWC 2009, Kenway et al. 2008).

These developments have introduced a growing range of sometimes conflicting pressures. With an increasing array of centralised and decentralised options under consideration, and an increasing level of complexity introduced by recycling based systems, there exists a need for systematic assessment of the tradeoffs associated with choosing alternative water cycle development pathways. The Life-cycle Assessment (LCA) methodology has been used to inform urban water cycle planning elsewhere in Australia, largely because of its capacity to take a long term view across a broad range of impacts for comparisons of dissimilar and complex options.

This study applies quantitative LCA to the urban water cycle infrastructure of the Gold Coast, as a starting point for analysis of the broader SEQ region. The first objective of this paper is to provide a snapshot of the life-cycle impacts associated with each element of the Gold Coast urban water cycle, in a way that is representative of a typical urban/industrial catchment in this region. By identifying the main contributors, a better understanding of opportunities to reduce these impacts will be reached. The second objective is to quantitatively consider the tradeoffs involved in different approaches to meeting domestic water and wastewater needs in this urban/industrial context.

METHODOLOGY

The analysis was undertaken by building detailed inventories of inputs and outputs for each of the water cycle components. Key data sources, and assumptions for each of the life-cycle stages (construction, use and disposal), are described in the following sections. The results of the inventory analysis are considered using a range of environmental and resource use indicators (impact categories). These steps were undertaken using the Simapro software (Simapro 2009).

System under consideration

This study is focussed on the provision of water supply and wastewater services, for a period of 50 years, to the customer base of Gold Coast Water (GCW). Included are those water supply and wastewater infrastructure types that, until recently, dominated the Gold Coast water cycle. These are: centralised water supply from dams and conventional water treatment plants (WTP); the use of domestic rainwater tanks; and centralised sewage collection, treatment and disposal. The Pimpama-Coomera Class A+ wastewater recycling scheme (for residential use) has also been included in the analysis. The recently commissioned Tugun seawater desalination plant, and other water supply possibilities flagged under the SEQ Water Strategy (QWC 2009), have not been included at this stage. These new water sources will be considered in more detail in the next stages of this project. Figure 1 illustrates the water cycle system under consideration.

Inventory data - Infrastructure

Most water cycle related LCA studies (e.g. Friedrich 2001, Gaterell et al. 2005) have found that the infrastructure operations dominate the results; with the construction phase making a small contribution, and the infrastructure end-of-life phase making only a minor contribution to the impacts. For this reason, infrastructure disposal has been excluded from the analysis, and construction inventories were based on other studies where local data was not readily available.

Inventories for the infrastructure construction included both the materials/ energy used and estimates of construction phase impacts. Multiple inventories are included for those infrastructure items where the lifespan is expected to be less than 50 years.

Detailed pipe length and materials data for the water supply, sewerage and recycling networks were obtained from GCW, with construction inventories for the pipe laying based on the work of Hallman et al. (2003). Construction inventories for the dams were based on information published by the Hinze Dam Alliance (2007). Data from Frischnecht et al. (2007) and Friedrich (2001) were used for the WTPs, STPs and AWTP. The number and size of installed domestic rainwater tanks was provided by GCW, with materials inventories based on the work of Grant & Opray (2005)

Inventory data – System operations

Modelling of the 'use phase' included the direct operational inputs and outputs for each infrastructure type. Unless stated otherwise, all operational data was collected for the 2007/08 financial year period.

For operation of the treatment plants (water and wastewater) and distribution networks (water, sewerage and recycling), inventories were

developed from detailed data provided by GCW. Inventories for the Pimpama-Coomera wastewater system were based on available data from Jan-June 2009. Estimates for fugitive NH₃, N₂O, CH₄ and non-biogenic CO₂ emissions from each STP followed the work of de Haas et al. (2009) and Foley et al. (in press).

Data on biosolids contaminant levels were provided by GCW, supplemented with extra analytes reported by Foley et al. (in press). To eliminate the influence of differing industrial inputs to each of the STP catchments, a weighted average of the different biosolids contaminant assays was assigned equally to each STP. For the same reason, estimates of treated wastewater metals and organic micropollutants were also assigned equally to each STP. In this case, the data was based on a hypothetical assay summarising the contaminants detected by Reungoat et al. (2009), Watkinson et al. (2009) and Farre Olalla (pers comms).

GCW provided data on the reuse of biosolids (100% used on agricultural lands), and inventories for the land application method were based on Foley et al. (in press). It was assumed that the bioavailable N and P loadings in land-applied biosolids would offset agricultural Urea and DAP usage. Estimates of metals contamination in these fertilisers were taken from Foley et al. (in press) for DAP, and Incitec Pivot (2010) for Urea. The assumption that 20% of biosolids carbon is sequestered follows de Haas et al. (2009).

On the advice of GCW, 20% of the treated effluent was taken as reused - mainly to irrigate golf courses, parks and canefields. The default source of water at these sites was assumed to be direct extraction from local freshwater streams. It was also assumed that the offsets from this source were only 33% of the total irrigated effluent flow, i.e. the availability of treated effluent means that irrigation at these sites is higher than would otherwise be. Given the low nutrient concentrations in the secondary effluent, it was assumed that only 50% of this N and P would offset fertiliser use in practice.

Household reuse of Class A+ effluent had not commenced at the time of this study – the modelling of hypothetical reuse flows is described in subsequent sections. No fertiliser offsets were ascribed to this reuse stream.

Assuming a well managed fertigation system is used for effluent irrigation, the risk of nutrient leaching or surface runoff was taken as negligible. On the contrary, to cater for poor irrigation management by households, it was assumed that 5% of effluent N and P would be lost to waterways where Class A+ water was used for external use. Nutrient losses to waterways for biosolids (6% of applied N, 5% of applied P) and fertiliser application (6.7% of applied N, 5.3% of applied P) followed default assumptions used in the ReCiPe model (Goedkoop et al. 2009). These assumptions on the

nutrient balance for land applied reuse (biosolids or wastewater) are all areas of large uncertainty.

Energy use for rainwater delivery systems can vary significantly, and there is limited data available on the full energy burden of rainwater systems. Our estimates were informed by the best available published data from Hood et al. (2010) and Retamal et al. (2009). It was assumed that none of these rainwater tanks used power intensive water sterilisation (such as UV).

Given the relatively high level of forestation in the catchments of the two dams in the Gold Coast region, estimates for dam methane emissions were based on overseas data for a dam in a forested tropical catchment (Delmas et al. 2005).

Maintenance inputs for the different infrastructure types were excluded.

Inventory data – lower order inputs

Second order inventories were included – these were the materials and energy flows associated with the manufacture, supply and/or processing of key inputs (e.g. concrete, chemicals, transport electricity) and any offsets (e.g. displaced fertiliser use). Data for these was sourced from the Australian LCA Database (Grant 2007) where possible, otherwise from the Ecoinvent database (Frischnecht et al. 2007). Third order inventories, such as the manufacture of the capital equipment used to provide chemicals and electricity, were excluded from the analysis.

Inventory data - Water balance

A water balance was constructed to marry all the key datasets available. Bulk mains supply data (from 2007/08) on residential consumption and losses (NWC 2009) was matched with the measured household mains use profiles (from 2008) of Willis et al. (2009a). This period coincided with a level of household water consumption that was notably lower than in previous and subsequent times.

The amount of rainwater used by Gold Coast houses with a rainwater tank (~15% of total houses) is not well understood. Beal et al (2010) estimated the effective mains water savings delivered by rainwater tanks that are plumbed for internal (toilet and laundry) and external uses, however it is likely that these represent only a small fraction of the total number of tanks at the Gold Coast. The more common configuration is for rainwater tanks to supply only external uses. The number of houses with each of these two configurations was estimated in conjunction with GCW. It was then assumed that rainwater tanks were sufficiently sized and configured to be able to meet all the demand for which they were connected. This simplistic assumption was used as a starting point in light of (a) the low household mains water use (~409L/hh/d) inferred by both the bulk mains supply and end-use datasets for the period in question;

and (b) the relatively high and regular rainfall received by most parts of the Gold Coast.

An estimate of the rainwater tank contributions to external water use was required to close the water balance. It was assumed that all houses used an equal baseline amount (regardless of source) for external purposes. This baseline (54L/hh/d) was then calculated by adjusting the rainwater tank contributions until a balance was obtained between the mains supply, mains use, and rainwater tank estimates.

Houses with a rainwater tank were then assumed to use additional rainwater for external purposes, above and beyond the baseline external usage. This assumption was also applied to the scenarios (see below) that included household reuse of Class A+ water. In both cases, the amount of additional external use (39L/hh/d) followed the predictions of Willis et al. (2009b).

Impact Assessment

This analysis follows the midpoint impact approach frequently used in other LCA studies. Midpoint indicators act as proxies for the potential of environmental impact, but do not attempt to predict the actual damage that might occur.

The basis for the selection of impact categories was the ReCiPe model (Goedkoop et al. 2009), which represents the most recent attempt to define a comprehensive set of indicators for LCA studies. The metrics provided in ReCiPe also represent the latest scientific developments in most cases, albeit with a focus on European conditions for some of the impact categories. Following the recommendations of ISO 14044 (2006), the selection of impact categories has been tailored to provide information most relevant to this case study.

Total *Freshwater Extraction (FWE)* from surface or underground water sources has been added, and is used as a surrogate for the potential risk to dependent aquatic ecosystems. Household rainwater diversions have been excluded from this metric, on the basis that: (a) there is evidence that urban rainwater capture can provide a positive ecological outcome for downstream waterways in Australian conditions (Walsh et al. 2005); and (b) there is no methodology available to integrate these different hydrological disruptions into a single indicator of ecological risk. Excluding household rainwater capture effectively means that it is treated as environmentally neutral. This is considered valid given the scale of total rainwater diverted to tanks is relatively small and distributed when compared to the dam-sourced extractions that feed the centralised water supply system at the Gold Coast.

Aquatic Eutrophication Potential (EP) provides an aggregated measure of the potential for oxygen depletion in receiving waters. The relative EP strengths of COD and species of nitrogen (N) and phosphorus (P) were taken from Kärman & Jönsson (2001). Fate factors for airborne N

emissions were taken from the ReCiPe defaults. Modelling of nutrient losses (to waterways and to the airshed) from land application systems is done at the inventory stage, rather than using the combined fate/effect factors proposed by ReCiPe. It was assumed that neither N nor P are strictly rate limiting on algal growth in receiving waters, as this provides a generic metric that acknowledges: (a) the range of freshwater, estuarine and coastal sewage discharge points in SEQ; (b) the suggestion by Abal et al (2005) that both nutrients can drive eutrophication in coastal receiving waters of SEQ; and (c) recent trends in STP nutrient discharge licensing. This assumption allowed the two eutrophication impact categories in ReCiPe to be merged into a single metric for use here.

Global Warming Potential (GWP) is a measure of the total greenhouse gas emissions, expressed in terms of equivalent CO₂ emissions. This analysis uses those ReCiPe model characterisation factors based on the most recent 100 year equivalency ratios published by the IPCC (2007).

All four of the toxicity impact categories from ReCiPe are used in this study – these are *Human Toxicity Potential (HTP)*, *Terrestrial Ecotoxicity Potential (TETP)*, *Freshwater Ecotoxicity Potential (FETP)* and *Marine Ecotoxicity Potential (METP)*. Because of the uncertainties in the underpinning toxicity modelling, ReCiPe provides three sets of characterisation factors for each of these metrics. The choice of set depends largely on the level of risk aversion that is appropriate for the study in question. Foley et al. (in press) found that metals releases to the environment typically dominate the toxicity impacts associated with wastewater systems; however concerns have been raised that LCA toxicological models tend to overstate the risks associated with these metals (Lighthart et al 2004). Consequently, the version (for each toxicity category) was chosen that provides the most conservative (lowest) impact assessments for metals releases.

Resource use was considered using the *Fossil Fuel Depletion (FFD)* metric from ReCiPe. This aggregates the inherent energy value of the different fossil stocks involved. The *Minerals Depletion* impact category is not used, as it does not consider Phosphorus depletion. Given the dominant role of urban water systems in the anthropogenic phosphorus cycle (Tangsubkul et al 2005), the *Minerals Depletion* metric (as it stands) would be of limited relevance to this case study.

These impact categories were chosen to reflect the most topical debates associated with the Australian urban water sector. The scope of future work will include additional impact categories that may also have relevance to urban water systems, such as those associated with phosphorus resource depletion and ozone layer depletion.

Analysis undertaken

The Gold Coast urban water cycle has been analysed in two stages.

Stage 1 investigates the scale of environmental and resource use impacts associated with the infrastructure stock for the Gold Coast urban water cycle, identifying the key contributors to each of these impacts. This essentially provides a snapshot of the 2008 operations, adjusted for inclusion of the Pimpama wastewater treatment process. Household recycling of Class A+ water was excluded from this analysis, as it was not commissioned at the time of this study.

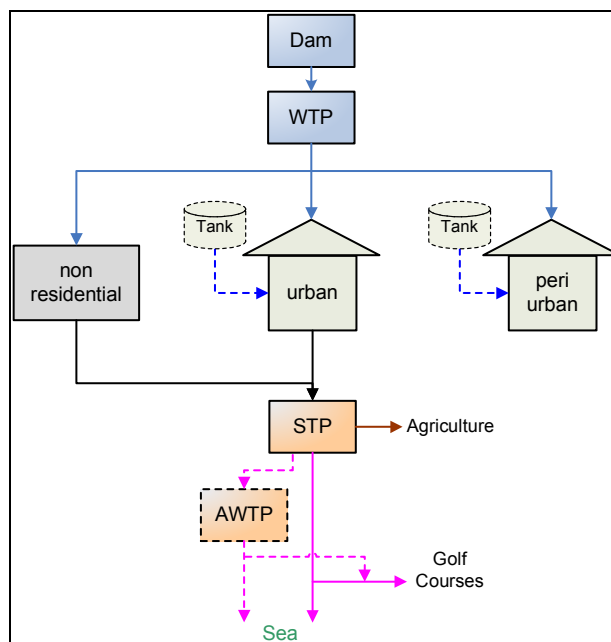


Figure 1: Gold Coast urban water cycle – system boundary for Stage 1 analysis

Because the vast majority of the Gold Coast households are serviced solely by the centralised water supply and wastewater systems, the results must be broken down to some common basis in order to explore the relative merits of the alternative approaches in use. **Stage 2** of the analysis does this, by comparing four different scenarios (see Figure 2 and Table 1) on the basis of a single household. These scenarios represent the range of household types (in terms of water services provision) in the urban area of the Gold Coast.

To get a representative indication of houses in the Pimpama Class A+ reticulation zone, Scenario 3 includes three important changes from the datasets used for the stage 1 analysis. Firstly, the Pimpama STP and AWTP models were modified to reflect an estimate for operations when running at full design load. This was because the plants are currently running at only a small fraction of their installed capacity, and are operating less efficiently than if fully loaded. Secondly, household reuse of Class A+ water was assumed to match the demands for toilet and external use. Thirdly, the amount of non-residential Class A+ reuse was changed to reflect the predictions of GCW.

The total impacts for each of the infrastructure components were allocated to the relevant household types. Most of the operational impacts were allocated across the four different population groups on a flow basis. The impacts associated with the infrastructure construction and dam methane emissions are independent of any marginal changes in flow, and therefore were allocated according to the number of households in each group. Estimates of housing numbers associated with each infrastructure type were taken from NWC (2009) for the centralised infrastructure, GCW data for rainwater tanks, and the design specifications for the Pimpama WWT system.

STAGE 1 RESULTS – EXISTING SYSTEM

Figure 3 breaks down the Stage 1 analysis by element of the urban water system. It shows that wastewater management (collection, treatment & disposal) makes the biggest contribution in most of the impact categories.

Table 2: Eutrophication Potential (EP) results

	EP (kt PO4 ⁻⁻⁻ eq)	
Total	22.7	(100%)
Effluent disposal	19.1	(84%)
Effluent reuse (golf courses, parks, agriculture)	0.0	(0%)
Biosolids to agriculture	4.8	(21%)
	leaching/runoff	19%
	NH3 vapours	2%
	transport	0%
Power generation	1.0	(4%)
	airborne NOx	4%
Offset fertiliser use	-2.6	(-12%)
	leaching/runoff	-10%
	NH3 vapours	<-1%
	manufacture	-1%
Other	0.4	(2%)

An interrogation of the results shows that the direct water cycle operations are the dominant cause of the *Freshwater Extraction* and *Eutrophication Potential (EP)* impacts. The water 'embedded' in power supply and other material inputs were insignificant, contributing less than 1% to the total result. Given our assumptions, the credit due to STP effluent recycled to irrigation is modest. Table 2 provides a breakdown of the EP results. While direct effluent emissions to the sea are the main contributor, our assumptions for leaching and runoff losses from biosolids led to an additional nutrient discharge equivalent to 19% of the total EP result. The transfer of gaseous N emissions (NH₃ from biosolids and NO_x from power generation) to waterways also makes a contribution. It should be noted that this result is based on European fate models, and their relevance to Australian conditions is uncertain.

The key contributors to the *Global Warming Potential (GWP)* results are illustrated in Table 3.

This profile indicates the points of greatest exposure to any economic changes resulting from the implementation of a carbon pricing regime in Australia. While direct power consumption constitutes 54% of the total, there are also significant contributions associated with fugitive emissions from the wastewater treatment system (21%) and from dams (7%). As the estimation of fugitive emissions is an area of significant uncertainty (de Haas et al. 2009, Foley et al. 2008), further research into these issues is warranted given their significant contribution to the greenhouse gas risk profile of the urban water sector. Chemicals use also makes a notable contribution (6%) to the GWP results, mostly associated with alum flocculants used in the mains water treatment process. Despite the nearly 7000km of pipelines included in the analysis, the greenhouse gas emissions 'embedded' in construction materials make only a 12% contribution to the total.

Table 3: results for Global Warming Potential (GWP) and Fossil Fuel Depletion (FFD)

	GWP (kt CO2 eq)		FFD (kt oil eq)	
Total	6268	(100%)	1113	(100%)
Power use	3362	(54%)	821	(74%)
	sewage	43%	sewage	59%
	water supply	10%	water supply	13%
	rain tanks	1%	rain tanks	2%
Fugitives (WW collection treatment & discharge)	851	(14%)		
	non-biogenic CO ₂	3%		
	N ₂ O	6%		
	CH ₄ (sewer)	4%		
Fugitives (dams)	406	(6%)		
	CH ₄	6%		
Chemicals use	415	(7%)	103	(9%)
	Al ₂ SO ₄	2%	Al ₂ SO ₄	2%
	Lime	2%	Lime	2%
	Caustic	1%	Caustic	1%
Biosolids & effluent reuse	682	(11%)	38	(3%)
	fugitives	7%		
	transport	4%	transport	3%
offset Fertiliser use	-213	(-3%)	-42	(-4%)
	supply	-2%	supply	-4%
	field fugitives	-2%		
Construction - Networks	724	(12%)	194	(17%)
	networks	7%	networks	12%
	other	5%	other	5%
Other	40	(1%)	-2	(0%)

Table 3 also breaks down the *Fossil Fuel Extraction* results, showing that black coal based power generation in Queensland is the dominant contributor.

Table 4 illustrates the key contributions to each of the toxicity impact categories. The results are separated into those associated with direct contributions from water cycle streams (land application of biosolids and effluent, and effluent discharge directly to waterways), and those incurred

more indirectly (via power generation, transport or the manufacture of materials).

The direct pathways make significant contributions to all but the *Human Toxicity Potential* results. Application of biosolids to agricultural land makes the biggest contribution to the *Terrestrial* and *Freshwater Ecotoxicity Potential* impact results, while effluent discharge is the most significant to the *Marine Ecotoxicity Potential* results. Of interest are the relatively small impacts ascribed to the significant proportion (~18% of total STP throughput) of effluent irrigation occurring at the Gold Coast. The results also suggest that it is metals, rather than organic micropollutants, that carry the biggest ecotoxicological risks in the discharge or reuse of water cycle wastes. Further work is required to determine whether the sample of organics in this study is representative of the full suite of micropollutants that have been identified in urban wastewater streams.

Table 4: breakdown of toxicity impacts

	Human Tox (HTP) (kt 1,4-DB eq)	Terrestrial Ecotox (TTP) (t 1,4-DB eq)	Freshwater Ecotox (FTP) (t 1,4-DB eq)	Marine Ecotox (MTP) (t 1,4-DB eq)
Total	197 (100%)	2287 (100%)	340 (100%)	2761 (100%)
Indirect pathways	191 (97%)	26 (1%)	55 (16%)	1932 (70%)
Biosolids to soil	5 (3%) Se 1% Hg 1%	2140 (94%) Cu 66% Zn 18% Hg 5% Se 4%	256 (75%) Cu 47% Se 18% Zn 5% Ni 4%	87 (3%) Cu 2% Se 2%
Effluent to soil	2 (1%) As 1%	98 (4%) V 1% Zn 1%	32 (10%) metals 5% chems 5%	10 (0%) metals <1% chems <1%
Effluent to sea	0 (0%) chems <1%	0 (0%) chems <1%	1 (0%) chems <1%	732 (27%) Mn 20% Ba 3% Pb 1% chems 2%
Fertiliser to soil (offset)	0 (0%) metals <1%	23 (1%) metals 1%	-4 (-1%) metals -1%	0 (0%) metals <1%

Tables 2-4 highlight some interesting issues associated with the reuse of biosolids and effluents. Firstly, the *EP* contribution of biosolids and effluent reuse (21% of total) is partially offset by that associated with the concomitant reduction in fertiliser use (-12% of total). If the biosolids and effluents were reused without garnering a fertiliser offset, then this would mean a significant increase in the overall nutrient discharge burden. Conversely, if the reuse application could deliver a net reduction in nutrient losses from heavily fertilised landscapes, then this could provide an avenue to reduce the overall nutrient discharge burden of the water cycle. Biosolids (an organic fertiliser) and wastewaters (applied as fertigation) may well offer this opportunity. These possibilities, and the uncertainties surrounding the nutrient loss pathways, suggest that the issue of nutrient land application warrants careful consideration in studies of the urban water system.

These same arguments apply also to the *GWP* results - although the offsets are relatively smaller because of the significant transport inputs and fugitive carbon losses associated with biosolids

disposal. Nonetheless, the significance of the biosolids fugitives (~7% of total *GWP*) highlights the importance of considering the type of land application. Finally Table 4 shows that the reduced heavy metals loadings (and associated toxicity impacts) in fertilisers are minor compared to the metals loadings associated with land application of biosolids and wastewaters.

STAGE 2 RESULTS – ALTERNATE SCENARIOS

Figure 4 compares the three alternative scenarios against the conventional household (scenario 0) that is serviced exclusively by centralised infrastructure. The results for Scenarios 1 & 2 highlight that the reduced *Freshwater Extraction (FWE)* achieved by rainwater tanks incurs an energy penalty when the alternative is a highly efficient, large scale centralised system based on low energy local dam supplies. This is reflected in the net increase in *Global Warming Potential (GWP)* and *Fossil Fuel Depletion (FFD)* results. The additional energy use also delivers increases in *Human Toxicity Potential (HTP)*, *Freshwater Ecotoxicity Potential (FETP)* and *Marine Ecotoxicity Potential (METP)*. These impacts are offset to varying degrees by the reduced chemicals usage for mains water treatment (resulting from the demand reductions). The *HTP* results are also influenced by the rainwater tank construction materials.

The results for Scenario 3 suggest that there may be limited value in following the Class A+ recycling model, if the alternative is a rainwater tank that is able to meet the full household demand for toilet, and external usage. Given this premise, no additional *FWE* benefit is delivered since the use of Class A+ water simply offsets the use of rainwater tank yield. Figure 4 also shows that Scenario 3 incurs significant additional *GWP*, *FFD*, *HTP*, *FETP* and *METP* impacts, over and above those associated with the rainwater tanks.

While the Class A+ recycling step is less energy intensive than the rainwater tank supply being offset by Scenario 3, its overall energy burden is higher. This is because all of the water is treated to Class A+ standard but only a relatively small fraction is reused. This comparison would change if a higher reuse percentage was made possible by higher household water demand. The other main contributor to the increased *GWP* and *FFD* results of Scenario 3 is the increased chemicals intensity of the Pimpama STP (compared to the STPs included in Scenarios 0-2) and the additional chemical usage of the Class A+ treatment step. The former is a function in part of (a) the pretreatment required for the Class A+ treatment step, and (b) the level of nutrient removal required for disposal of surplus effluent.

The increased *HTP* result for Scenario 3 is mostly associated with the materials intensity of the additional treatment plant and piping network

required for Class A+ recycling. This also makes a contribution to the increased *FETP* result, with the other significant contributor being the runoff associated with household effluent irrigation. This recycling does mean a significant reduction in the *METP* results for scenario 3 (because of reduced estuarine effluent discharge), however this is more than offset by the increased need for construction materials, power and chemical use. The small decrease in *TETP* results is associated with the Pimpama plant having a marginally smaller rate of biosolids generation than the average of the other STPs.

Scenario 3 does deliver significant *Eutrophication Potential* reductions, although reuse is not that influential to this result given the low demand for household and non-domestic irrigation of Class A+ water that underpins this analysis. Instead, the majority of the difference can be ascribed to the Pimpama STP achieving much lower effluent nutrient concentrations than the weighted average for the rest of the Gold Coast STPs. As described above, these low secondary effluent nutrient levels carry significant energy and chemicals use burdens. The merits or otherwise of this trade-off would depend on whether the low secondary effluent nutrient levels are required to facilitate the large scale adoption of recycling for irrigation. More accurate accounting of the nutrient leaching/runoff risks (associated with effluent reuse by irrigation) would therefore enhance an assessment of the Scenario 3 model.

These irrigation risks would become even more relevant if the household irrigation demand were to increase in line with the recent growth in per capita potable water consumption noted at the Gold Coast. Increased household water usage would also increase the likelihood that a 5kL rainwater tank (the minimum size allowed for new houses in SEQ) could not fully meet this demand over the long term. A rainwater shortfall would result in the Class A+ model (Scenario 3) delivering a net *Freshwater Extraction* benefit when compared with a house serviced only by a rainwater tank (Scenario 2).

CONCLUSIONS

For the urban water system considered in this analysis, the wastewater management step makes the biggest contribution to the life cycle impacts involved. Efforts to improve the performance of wastewater systems will therefore be beneficial in terms of reducing the environmental burden of the overall urban water cycle.

The LCA methodology provides a useful mechanism for quantifying the greenhouse gas risk profile of the urban water sector, showing here that electricity use, fugitive gases, and chemicals usage are the biggest points of exposure to any changes that might result from carbon constraints on the economy. Both the alternative forms of residential water supply considered in this study showed an

increased greenhouse gas burden when compared with the traditional low energy dam-based model. For the household scale rainwater tanks this was due to higher energy intensity. However there is large uncertainty associated with the energy burden of rainwater tank systems, which can vary widely depending on a range of factors associated with climate, system configuration, and pumping system design. For cluster scale Class A+ recycling, the increased energy and chemicals usage were the cause. These conclusions might not hold if the benchmark is taken as the relatively energy intensive large scale water supply options (seawater desalination and indirect potable reuse) also being considered in SEQ.

While STP discharges were the main source of nutrients to waterways, the nutrient leaching and runoff risks associated with the land application of biosolids and/or effluents should not be overlooked. Estimates of the latter are subject to large uncertainties. Consideration of this pathway might account for significant increases or decreases in the overall eutrophication risk to waterways, depending on the ability of these reuse streams to offset the associated risks with synthetic fertiliser use.

The results also provide some guidance on the toxicity risk profile associated with the urban water cycle. Land application of biosolids and marine discharge of effluent both made significant contributions to the toxicological impact results. The lesser significance of effluent recycling, and of organic micropollutants more generally, was noted. These aspects warrant further investigation, given the growing interest in wastewater recycling as a means to supplement urban water supplies. The analysis also highlighted the potential toxicity risks associated with the increased energy, chemicals and materials intensity of the non-conventional water cycle configurations considered here.

Given the low household demand profile that underpinned this analysis, household reuse of Class A+ water delivered little direct benefit in the impact categories associated with the protection of aquatic ecosystems. The chemical and power usage required for the extra treatment resulted in a notable increase in greenhouse gas emissions. However, higher household demands would likely make the recycling of Class A+ water more attractive when compared to the household model with rainwater tanks as the only alternative water source. This sensitivity suggests that a range of household water demand profiles should be considered when comparing alternate water cycle systems.

The analysis has highlighted the benefits of considering both the whole water cycle, and the full life-cycle of all key system flows, when assessing urban water cycle systems. Rigorous quantification across a broad range of impact categories helps to reveal a range of sometimes complex tradeoffs when comparing alternatives. It also allows the

identification of key data gaps that will be critical to multi-criteria environmental optimisation for water cycle planners.

ACKNOWLEDGMENT

We are extremely grateful to a number of staff of Gold Coast Water who provided data, in particular Kelly O'Halloran, Mark Wilson, Anna Hollingsworth, Tamara Bauld and Rachelle Willis. We would also like to thank Jeff Foley (GHD), Al Grinham (UQ), Cara Beal (GU), Brad Sherman (CSIRO) and Ted Gardner, Barry Hood and Alison Vieritz (DERM) for their guidance on a range of technical matters.

REFERENCES

- Beal, C., Gardner, T., Sharma, A. 2010. Can mandated domestic rainwater tanks in SEQ deliver the expected savings of 70kL/hh/y, Ozwater'10, Brisbane, 8-10 March 2010.
- De Haas, D., Foley, J., Lant, P. 2009. Energy and greenhouse footprints of wastewater treatment plants in south-east Queensland, Ozwater'09, Melbourne, 16-18 March 2009.
- Delmas, R. et al. 2005, 'Long Term Greenhouse Gas Emissions from the Hydroelectric Reservoir of Petit Saut (French Guiana) and Potential Impacts' in A. Tremblay (ed), *Greenhouse Gas Emissions - Fluxes and Processes*. Springer, Heidelberg, pp.293-312.
- Farre Olalla, M., 2009 pers comms.
- Foley, J., Lant, P. & Donlon, P. 2008. Fugitive greenhouse gas emissions from wastewater systems. *Water*, 38(2): 18-23.
- Foley, J., de Haas, D., Hartley, K. & Lant, P. in press. Comprehensive Life Cycle Inventories of Alternative Wastewater Treatment Systems. *Water Research*.
- Friedrich, E 2001, Environmental Life Cycle Assessment of Potable Water Production, MSc thesis, University of Natal, Durban.
- Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Heck, T., Hellweg, S., Hischer, R., Nemecek, T., Rebitzer, G., Spielmann, M. & Wernet G. 2007. Overview and Methodology. ecoinvent report No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, 2007.
- Gaterell, M.R., Griffin, P., Lester, J.N. 2005. Evaluation of environmental burdens associated with sewage treatment processes using life cycle assessment techniques. *Environmental Technology*, 26(3), 231-249.
- Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. & van Zelm, R. 2009. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition. Report I: characterisation. VROM, Den Haag, The Netherlands
- Grant, T., Opray, L., 2005. LCA report for sustainability of alternative water and sewerage servicing options. Yarra Valley Water. <http://www.yvw.com.au/yvw/Home/AboutUs/ReportsAndPublications/ResearchPublications.htm>
- Grant, T. (ed) 2007. Australian LCA Data Library. Centre for Design, RMIT, Melbourne.
- Hallmann, M., Grant, T., Alsop, N. 2003. Life cycle assessment and life cycle costing of water tanks as a supplement to mains water supply, Yarra Valley Water 2003. Accessed at <http://www.yvw.com.au/yvw/Home/AboutUs/ReportsAndPublications/ResearchPublications.htm> December 2008
- Hinze Dam Alliance, 2007. Hinze Dam Stage 3 Environmental Impact Statement, Accessed at: http://www.hinzedamstage3.com/public_notices_publications.php#5 12 November 2008
- Hood, B., Gardner, T., Barton, R., Gardiner, R., Beal, C., Hyde, R. & Walton, C. 2010. The Ecovillage at Currumbin – a model for decentralised development, Ozwater'10, Brisbane, 8-10 March 2010.
- Huijbregts, M. A. J., Seppala, J. 2001. Life Cycle impact assessment of pollutants causing aquatic eutrophication. *International Journal of Life Cycle Assessment* 6(6): 339-343
- Incitec Pivot, 2010. Product Label for Granular Urea, Accessed at: http://www.incitecpivotfertilisers.com.au/product_search.cfm?ProductId=738&action=viewproduct
- IPCC 2007. Climate Change 2007: The Physical Science Basis. [Solomon, S.D. et al. (eds)]. Cambridge University Press, UK.
- Kärroman, E., Jönsson, H. 2001. Including oxidisation of ammonia in the eutrophication impact category. *International Journal of Life Cycle Assessment* 6(1): 29-33.
- Kenway S., Priestley A., Cook S., Seo S., Inman I., Gregory M. and Hall M. 2008. Energy Use in the Provision and Consumption of Urban Water in Australia and New Zealand. Water Services Association of Australia, CSIRO, Melbourne.
- Lighthart T. et al. 2004. Declaration of Appeldoorn on LCIA of Non-Ferrous Metals. Available at http://www.leidenuniv.nl/cml/ssp/projects/declaration_of_apeldoorn.pdf
- NWC, 2009. National Performance Report 2007-08: urban water utilities. National Water Commission, Canberra.

Queensland Development Code part MP 4.2 – Water Savings Targets. Accessed at <http://www.dip.qld.gov.au/building/current-parts.html> April 2008

QWC 2009. South East Queensland Water Strategy: Revised Draft 2009, Queensland Water Commission, Brisbane.

Retamal M., Turner A. and White S. 2009. Energy implications of household rainwater systems, *Water*, 36(8): 70-75.

Reungoat, J., Macova, M., Escher, B., Carswell, S., Mueller, J. & Keller, J. 2009, Removal of micropollutants and reduction of biological activity in a full scale reclamation plant using ozonation and activated carbon filtration, *Water Research*, In Press, DOI: 10.1016/j.watres.2009.09.048.

Simapro® 2009. Simapro Software v.7.1.8. PRé Consultants, The Netherlands. <http://www.pre.nl/>

Tangsubkul, N., Moore, S. & Waite, D. 2005. Incorporating phosphorus management

considerations into wastewater management practice. *Enviro. Science and Policy* 8:1-15.

Walsh, C.J., Fletcher, T.D., Ladson, A.R. 2005. Stream restoration in urban catchments through redesigning stormwater systems: Looking to the catchment to save the stream. *Journal. North. American. Benthological Society*. 24(3):690–705

Watkinson, A., Murby, E., Kolpin, D. & Costanzo, S. 2009, The occurrence of antibiotics in an urban watershed: From wastewater to drinking water, *Science of the Total Environment*, In press. DOI: 10.1016/j.scitotenv.2008.11.059.

Willis, R., Stewart, R.A., Panuwatwanich, K., Capati, B. & Giurco, D. 2009a, Gold Coast Domestic Water End Use Study, *Water*, 36(6): 84-90.

Willis, R., Stewart, R.A., & Emmonds, S. 2009b. Pimpama-Coomera dual reticulation end use study: baseline situational context and post-commission end use prediction, Reuse09, Brisbane, 21-25 September 2009.

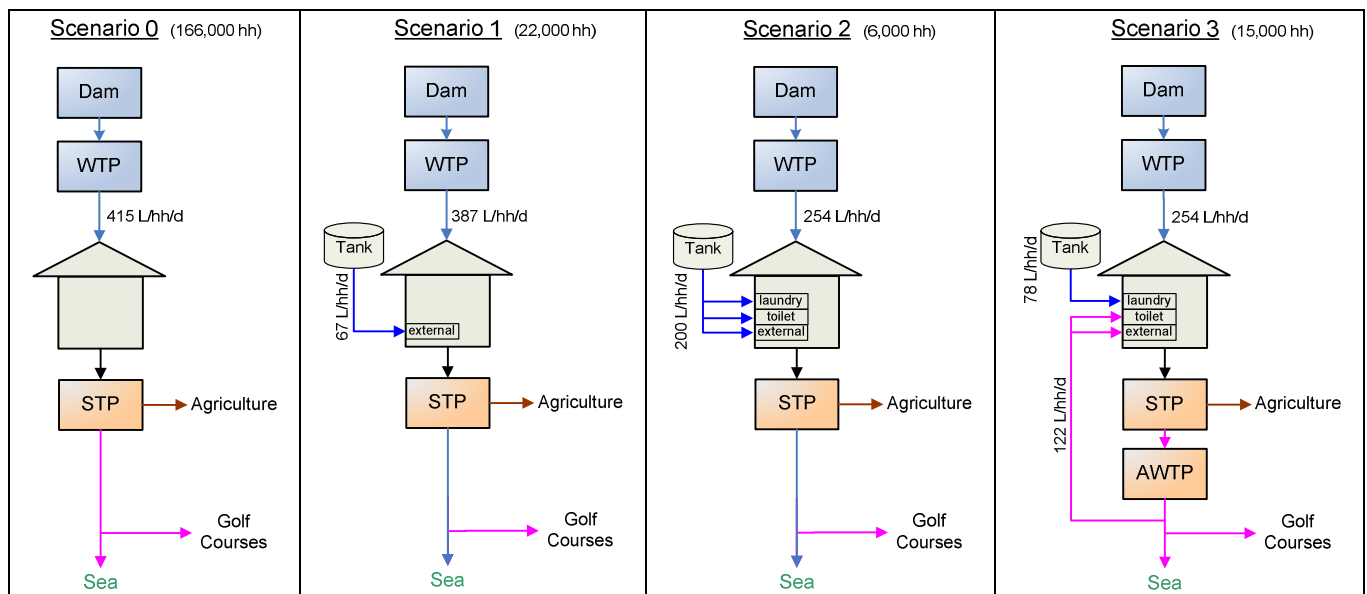


Figure 2: Household scenarios for Stage 2 analysis

Table 1: Household scenarios for Stage 2 analysis

Scenario 0	Scenario 1	Scenario 2	Scenario 3
The traditional centralised infrastructure approach, utilising local dam-based water supplies and large scale STPs that discharge 80% of the treated effluent to waterways. This reflects the majority of existing houses on the Gold Coast.	Centralised infrastructure supplemented with a household rainwater tank directed to outdoor household use. This reflects the majority of those houses that have installed a rainwater tank under the government tank retrofit programs of recent years.	Centralised infrastructure supplemented with a household rainwater tank directed to toilet, laundry (cold water only) and outdoor household use. This rainwater tank configuration is now compulsory for all new housing in the SEQ region (<i>Queensland Development Code part MP4.2</i>).	The planned system for the Pimpama-Coomera scheme - new houses will have their sewage reticulated to a local STP, treated to class A+, then reticulated back for toilet flushing & outdoor use. Each house will also have a rainwater tank directed to the cold water laundry demands and to external taps. The mooted aquifer storage system was not considered.

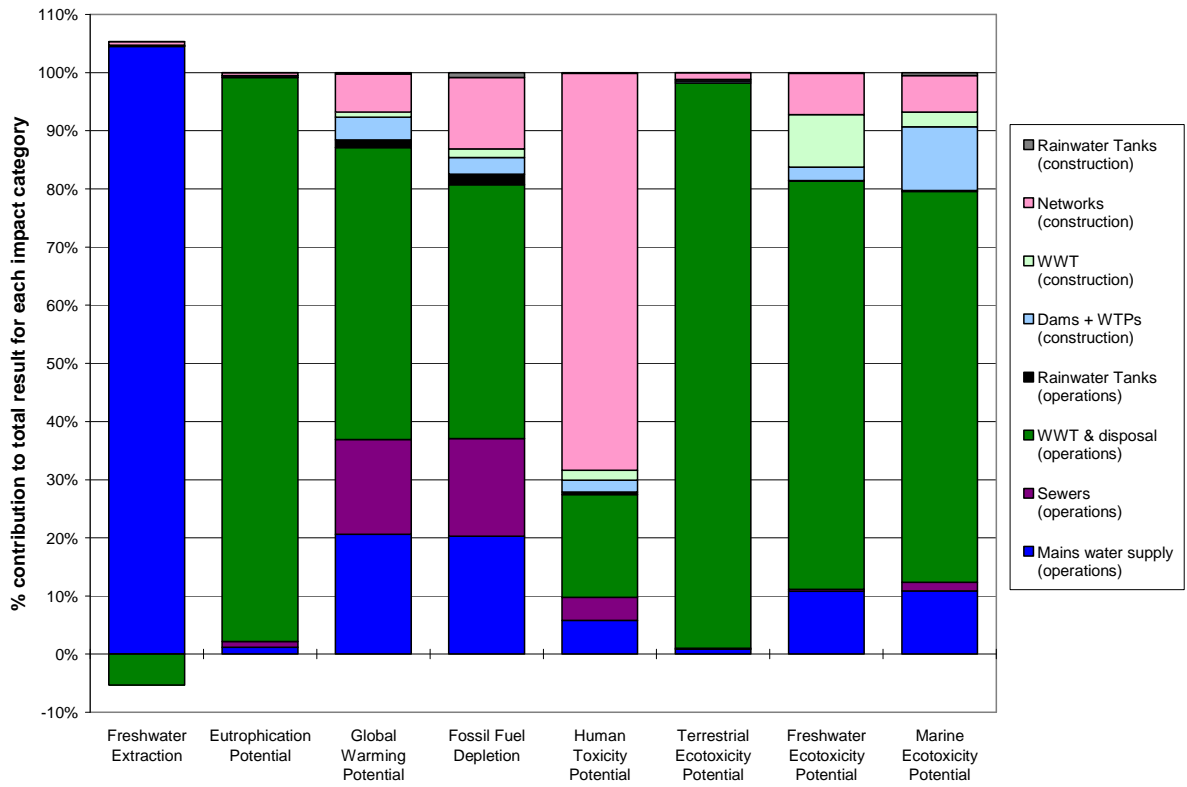


Figure 3: Snapshot results

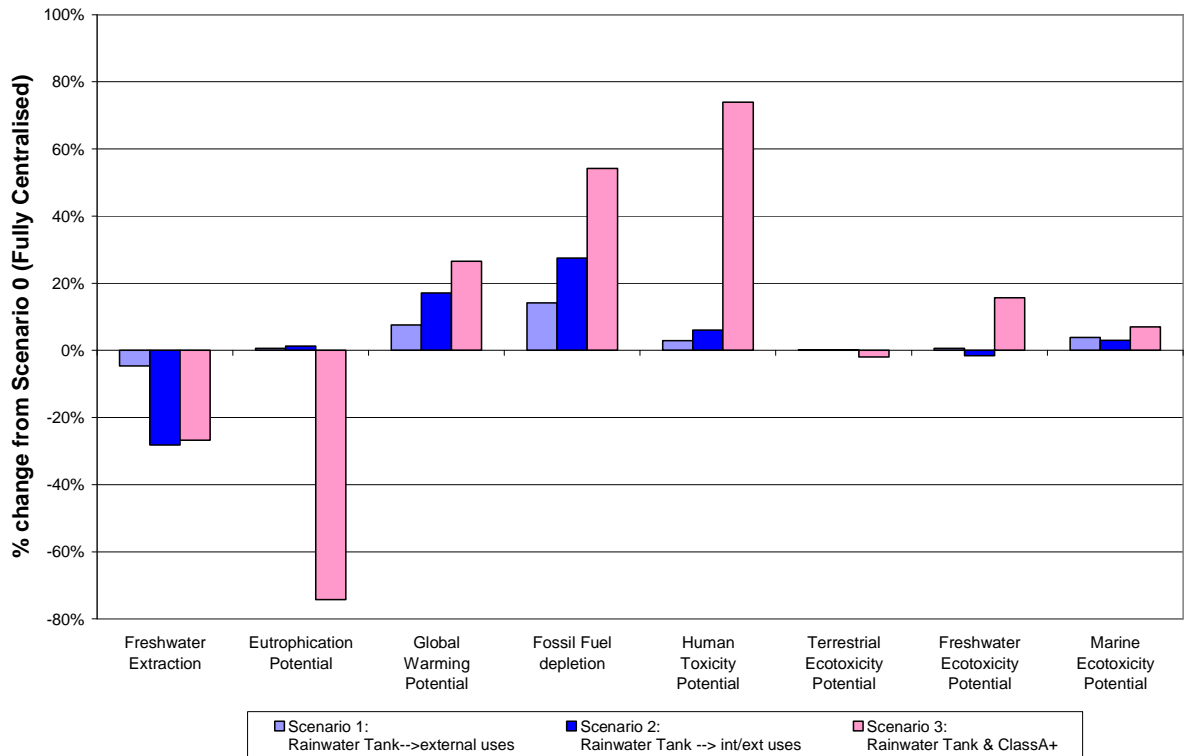


Figure 4: household scenario comparisons – relative to Scenario 0