

# Life Cycle Assessment of Biological Nutrient Removal Wastewater Treatment Plants

Jeff Foley\*, David de Haas\*, Ken Hartley\*\*, Paul Lant\*

\*Advanced Wastewater Management Centre; \*\*Ken Hartley Pty Ltd

\*University of Queensland, St Lucia 4072, Australia; \*\* F1c 235 Forest Lake Blv, Forest Lake 4078, Australia  
[jeff.foley@awmc.uq.edu.au](mailto:jeff.foley@awmc.uq.edu.au)

**Keywords:** wastewater, biological nutrient removal, anaerobic treatment, life cycle assessment

## ABSTRACT

Advances in wastewater treatment over the past 150 years have improved public health and local water quality. Recently however, society has begun to consider the wider environmental implications of these improvements. This paper uses life cycle assessment to quantitatively compare the environmental costs and benefits of different wastewater treatment technologies and standards. It is demonstrated that there exists a broader environmental trade-off for advanced nutrient removal, that can only be justified by society implicitly placing higher value on local water quality, than on global environmental pressures (e.g. climate change). The global costs of achieving lower levels of effluent nutrients become increasingly larger and may outweigh the local benefits arising from improved water quality. It is also demonstrated that anaerobic treatment of domestic wastewater, with energy recovery, provides better environmental outcomes than “leading edge” aerobic nutrient removal methods.

## Introduction

Since the mid-19th century, societies have dramatically increased the level of public health by the appropriate separation and treatment of human wastes. In recent times, urban authorities have also endeavoured to improve local water quality by advanced forms of wastewater treatment, such as biological nutrient removal (BNR). These advances in technology are a clear success in public health security and water quality protection. Recently however, society has begun to consider the wider environmental implications of these efforts to improve local water quality, and found that the ability of the water industry to quantitatively assess the environmental burdens associated with wastewater treatment is fairly limited. This paper uses life cycle assessment (LCA) to quantitatively compare the environmental costs and benefits of different wastewater technologies.

## LCA Goal and Scope Definition

The goal of this study is to quantitatively evaluate 34 different wastewater treatment scenarios, to identify which configuration has the lowest overall environmental impact. These scenarios cover eight wastewater treatment plant (WWTP) configurations, targeting a range of effluent qualities:

- Case 0 – “Do Nothing” base case.
- Case 1 – Primary sedimentation + anaerobic digestion (inc. heat/energy recovery).
- Case 2 – Primary sedimentation + activated sludge plant (no nitrification) + anaerobic digestion (inc. heat/energy recovery).
- Case 3 – Primary sedimentation + activated sludge plant (nitrification only) + anaerobic digestion (inc. heat/energy recovery).
- Case 4 (six sub-cases of different effluent qualities) – Primary sedimentation + Modified Ludzack Ettinger (MLE) BNR activated sludge plant + anaerobic digestion (inc. heat/energy recovery):
  - a) TN<20, TP<5
  - b) TN<10, TP<5
  - c) TN<5, TP<5
  - d) TN<20, TP<1
  - e) TN<10, TP<1
  - f) TN<5, TP<1
- Case 5 (six sub-cases of different effluent qualities) – Oxidation Ditch BNR (extended aeration) plant + covered sludge storage lagoon (inc. energy recovery):

- a) TN<10, TP<5
- b) TN<5, TP<5
- c) TN<3, TP<5
- d) TN<10, TP<1
- e) TN<5, TP<1
- f) TN<3, TP<1
- Case 6 (six sub-cases of different effluent qualities) – 5-Stage Bardenpho BNR (extended aeration) plant + covered sludge storage lagoon (inc. energy recovery):
  - a) TN<10, TP<5
  - b) TN<5, TP<5
  - c) TN<3, TP<5
  - d) TN<10, TP<1
  - e) TN<5, TP<1
  - f) TN<3, TP<1
- Case 7 (six sub-cases of different effluent qualities) – 4-Stage Membrane Bioreactor (MBR) BNR (extended aeration) plant + covered sludge storage lagoon (inc. energy recovery):
  - a) TN<10, TP<5
  - b) TN<5, TP<5
  - c) TN<3, TP<5
  - d) TN<10, TP<1
  - e) TN<5, TP<1
  - f) TN<3, TP<1
- Case 8 (six sub-cases of different effluent qualities) – Anaerobic primary treatment (inc energy recovery) + 5-Stage Bardenpho BNR (extended aeration) plant + covered sludge storage lagoon (inc. energy recovery):
  - a) TN<10, TP<5
  - b) TN<5, TP<5
  - c) TN<3, TP<5
  - d) TN<10, TP<1
  - e) TN<5, TP<1
  - f) TN<3, TP<1

**Functional Unit**

The primary function of a WWTP is to remove contaminants from the wastewater for appropriate disposal. Secondary functions include producing biosolids, and possibly electricity. The functional unit for this study is:

*The treatment and disposal of 10 ML/d of raw domestic wastewater of typical composition for the life of the plant (i.e. 15 years). Disposal of resulting biosolids must also be in compliance with “Class B” regulations for agricultural land application.*

In all scenarios, it is assumed that effluent is disposed to an environmentally sensitive estuarine environment; and sludge is mechanically dewatered, with the biosolids being transported for farmland application, at a fixed distance (200km) from the plant. Fifteen years is chosen as a typical WWTP life between upgrades.

**System Boundary**

The system boundary (refer Figure 1) includes first-order environmental impacts, such as direct atmospheric emissions and effluent discharges. It also includes second-order impacts, such as the emissions and resources required for electricity generation and chemicals manufacture.

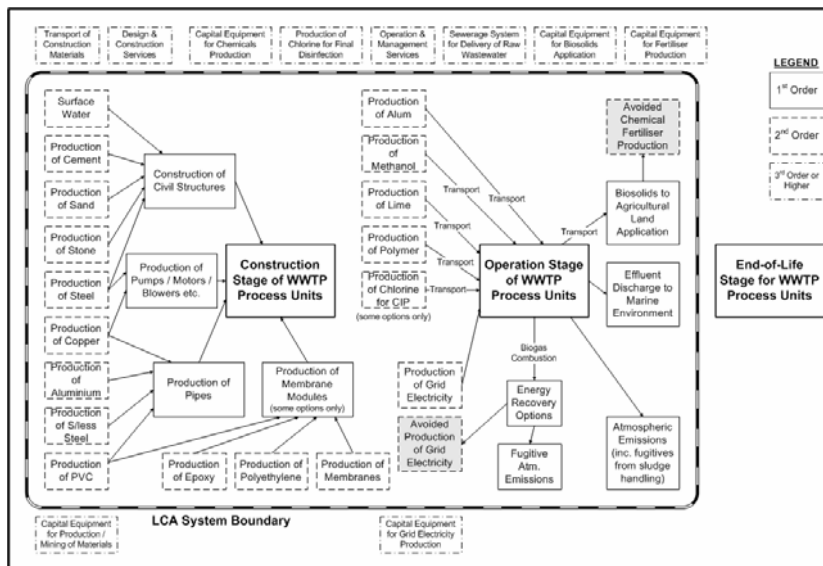


Figure 1: System Boundary

Only construction and operating phases are considered. End-of-life phase impacts are not included because they

are generally negligible, when compared with the operating and construction phases [1][2][3]. Where biosolids are used as fertiliser, the avoided impacts of chemical fertilisers are credited to the system. Similarly, where electricity is produced from biogas, the avoided impacts of Australian grid electricity are credited to the system.

### Life Cycle Inventory Analysis

The WWTP scenarios have been rigorously constructed using the BioWin™ biological simulation package, proven engineering design methods and the collective 80 years of experience amongst the co-authors. This exercise provides the input data for the operating phase of the LCI, such as:

- Biosolids – avoided chemical fertiliser (kg); transportation (tonne.km) and fuel usage for biosolids application (MJ); and NH<sub>3</sub> and N<sub>2</sub>O emissions (kg) and (some) metal emissions (e.g. aluminium for chemical phosphorus precipitation) (kg).
- Chemical consumption – alum, lime, methanol, polymer, chlorine (for clean-in-place) (kg); and Transportation of chemicals (tonne.km).
- Atmospheric emissions (kg) – CH<sub>4</sub>, N<sub>2</sub>O, NH<sub>3</sub>, SO<sub>x</sub>, NO<sub>x</sub>, CO, CO<sub>2</sub> (oxidation of imported methanol).
- Land occupation (m<sup>2</sup>.yr); and
- Energy consumption (kWhr).

The construction phase inventory data is based on an LCA of three Swiss treatment plants [4]. Where possible, data from the Australian LCA database [5] have been used, but when it has been necessary to import data from European databases, these have been modified to include the Australian energy mix and transportation patterns.

### Life Cycle Impact Assessment (LCIA)

This study adopts a modified version of the IMPACT 2002+ LCIA method [6].

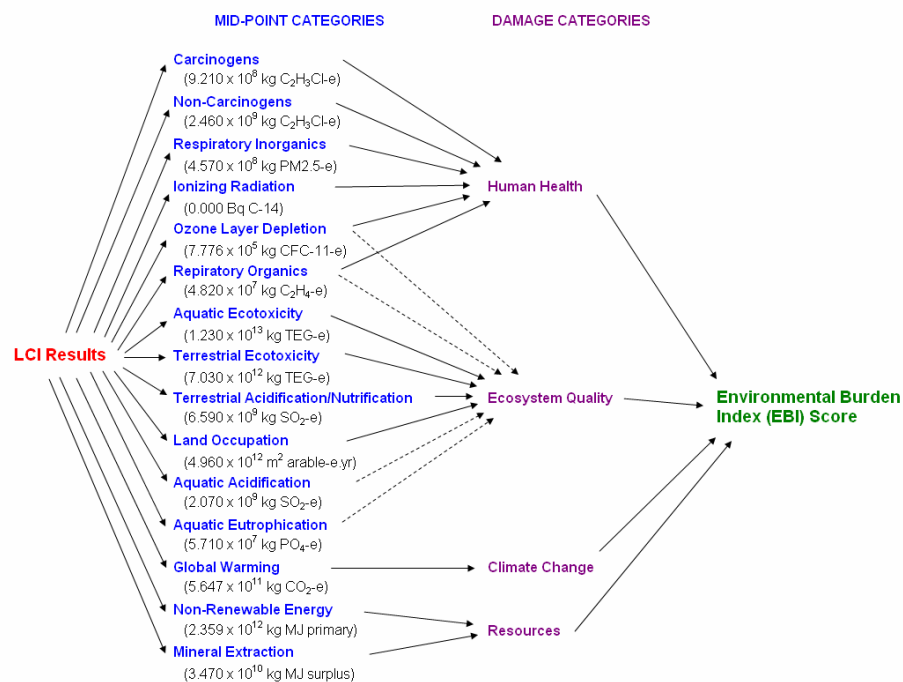


Figure 2: IMPACT 2002+ Life Cycle Impact Assessment Framework and Estimated Annual Environmental Emissions for Each Mid-Point Category in Australia (figures in brackets)

Some modifications and limitations of the IMPACT 2002+ LCIA method must be noted:

- The mid-point Eutrophication Potentials (EPs) have been updated to account for primary oxygen consumption in nitrification [7] and world-based emission fate factors [8]. The EPs also assume a 50% N-limited / 50% P-limited aquatic receiving environment.

- IMPACT 2002+ adopts a 500 year horizon for global warming potentials (GWPs) to take full account of the long-term, integrated effects of climate change [6]. For this study, GWPs have been modified to the 100 year horizon, as published by the Intergovernmental Panel on Climate Change [9]. This compromises between capturing the long-term effects of climate change, and the much shorter time frames for policy-making and budgeting.
- IMPACT 2002+ does not include a damage model for aquatic eutrophication and acidification. This is a significant gap in LCIA damage modelling for WWTPs, and is being addressed in current revisions to IMPACT 2002+, and other methods. With this present limitation, damage assessment can only be applied to scenarios that have equivalent effluent quality (i.e. eutrophication damage impacts from compared scenarios are equivalent and hence to do not influence the relative comparison).
- All of the fate and exposure modelling done for IMPACT 2002+ is based on broad European conditions.
- Similarly, there is no explicit fate modelling for eutrophication/acidification effects in a particular aquatic receiving body. This is a potential area for future research and adaptation of the underlying LCA models to fit specific local environments and receiving water bodies.
- Results are normalised against an estimate of the Australian environmental profile (Figure 2).

### Mid-Point Assessment

The modified IMPACT 2002+ method was applied to the 34 WWTP scenarios. Figure 3 compares all scenarios when the normalised impact categories are aggregated, without any weighting. This gives each scenario a single Environmental Burden Index (EBI) score. Based on this un-weighted mid-point comparison:

- The “Do Nothing” scenario is the worst environmental outcome.
- BNR does not necessarily provide a better environmental outcome than “basic” treatment, but it does significantly improve local water quality. Improvements in the environmental performance of BNR technologies would make them more beneficial from both local and global perspectives.
- Improving local water quality by chemical phosphorus removal is not justified on broader global environmental indicators.
- There is no significant global environmental benefit in lower effluent nitrogen concentrations.

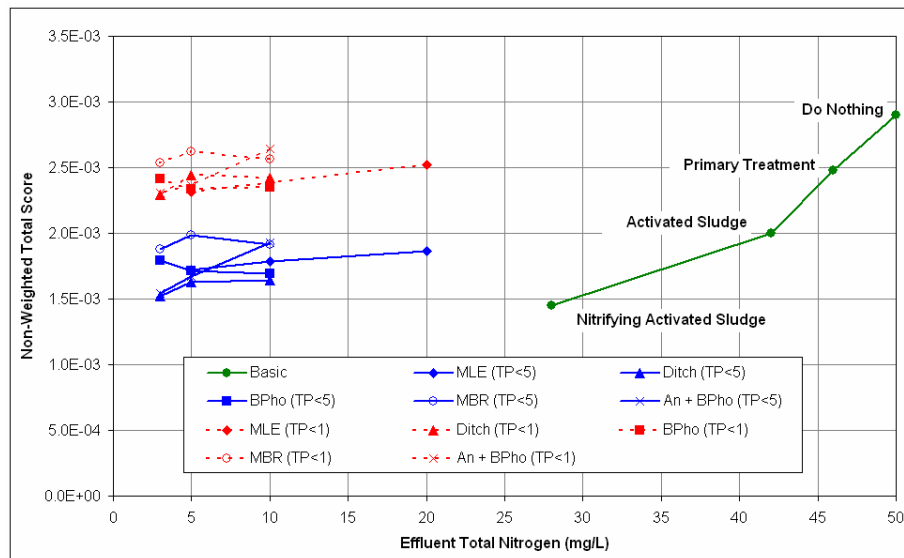


Figure 3: Non-weighted total of normalised mid-point LCIA categories for all 34 scenarios

These conclusions do not align with the current regulatory paradigm in Australia, or with society’s general expectations – i.e. we place more value on our local water bodies than we do on the global environment. To reflect this prevailing societal attitude, the categories of Aquatic Eutrophication and Acidification can be weighted more heavily. Figure 4 demonstrates that these categories must be weighted 5 times higher than the other LCIA categories to justify BNR on global environmental grounds. Even despite this increased weighting,

the slopes of the EBI curves remain relatively flat as the effluent TN decreases below 20 mg/L. This demonstrates that as effluent TN concentration decreases, the marginal improvement in local water quality is not matched by the marginal improvement in the broader EBI score. The trade-off between improved local water quality and broader environmental burden is more onerous at lower effluent TN concentrations.

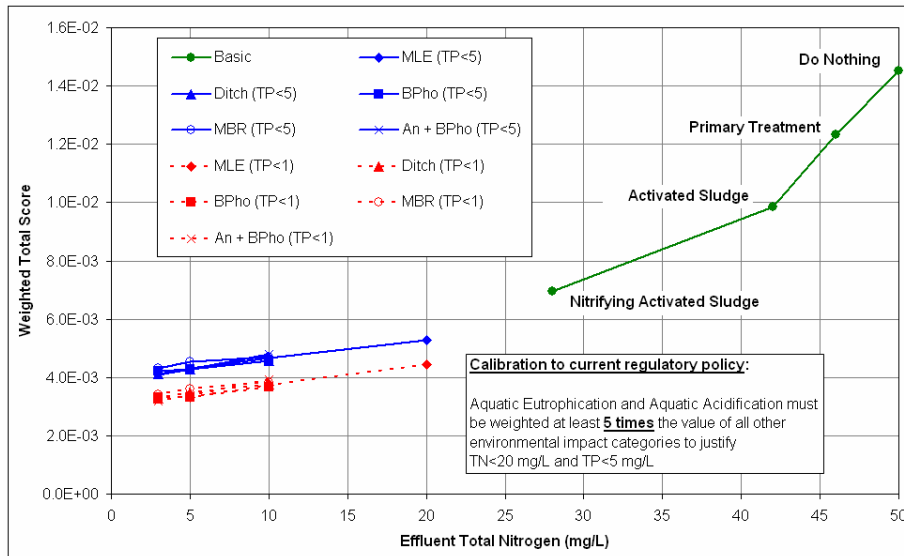


Figure 4: Weighted total of normalised mid-point LCIA categories for all 34 scenarios

### End-Point / Damage Assessment

The IMPACT 2002+ method does not include a damage model for Aquatic Eutrophication or Acidification. However, damage LCIA is possible by only comparing scenarios with the same effluent quality so that the environmental damage due to Aquatic Eutrophication and Acidification is the same for all options, and does not influence the relative comparison. Figure 5 displays this comparison for the BNR configurations at an effluent quality of TN<10mg/L and TP<5mg/L. The four “damage” categories have been aggregated, without weighting.

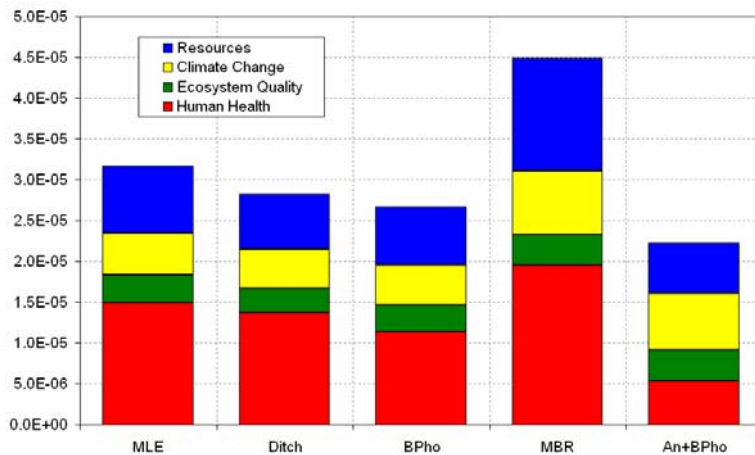


Figure 5: Non-weighted total of normalised “damage” LCIA categories for five BNR configurations at TN<10 mg/L, TP<5 mg/L

From this assessment, the following conclusions are drawn:

- The MLE, Oxidation Ditch and 5-Stage Bardenpho processes are roughly equivalent, except for Human Health. Overall, a slight advantage is shown for the compartmentalised Bardenpho configuration (using diffused aeration), over the oxidation ditch configuration (using mechanical surface aerators), and the MLE configuration (using diffused aeration).

- The MBR process scores poorly, due to high energy and chemical consumption.
- The anaerobic treatment process, with 5-Stage Bardenpho post-treatment for nutrient removal, scores particularly well for Human Health and Resources. This is mainly due to lower power consumption, and the avoided emissions from coal-fired power generation. However, the results for Climate Change are adversely influenced by the assumption that dissolved methane in the anaerobic effluent is stripped to the atmosphere in the downstream aerated zones of the WWTP. Despite this onerous assumption, the anaerobic-based treatment configuration has a lower environmental burden than the next closest BNR technology by approximately 15%.

## Conclusions

This quantitative LCA of various WWTP configurations demonstrates that the most environmentally sound option is not necessarily at the limit of “best practice” for nutrient removal. There exists a broader environmental trade-off for advanced nutrient removal, that can only be justified by society implicitly placing higher value on local water quality, than on global environmental pressures (e.g. climate change). The environmental costs of achieving higher levels of nutrient removal become increasingly significant and may outweigh the local benefits arising from improved water quality. These findings are very significant, particularly given increasing public awareness of global environmental issues. Regulatory agencies should reconsider their water quality protection strategies, since the current paradigm for WWTPs has a singular focus on effluent quality, without considering the broader environmental consequences of the treatment required to meet these stringent limits. Furthermore, domestic wastewater treatment, based primarily on anaerobic processes with energy recovery, potentially provides better environmental outcomes than “leading edge” extended aeration BNR methods. This is true even when the anaerobic systems are complemented with chemically-assisted, aerobic post-treatment so as to achieve the same level of nutrient removal as the comparable extended aeration BNR processes. This study helps inform water authorities and regulatory agencies for future policy and funding strategies. A shift towards anaerobic treatment is justified on the basis of whole-of-plant life cycle considerations, even when increased importation of chemicals is necessary to improve nutrient removal.

## References

- [1] Emmerson, R. H. C., Morse, G. K., Lester, J. N., and Edge, D. R. (1995). The Life-Cycle Analysis of Small-Scale Sewage Treatment Processes. *Journal of Chartered Institution of Water & Environmental Management*, 9(3), 317-325.
- [2] Zhang, Z., and Wilson, F. (2000). Life-cycle assessment of a sewage-treatment plant in South-East Asia. *Journal of the Chartered Institution of Water and Environmental Management*, 14(1), 51-56.
- [3] Gaterell, M. R., Griffin, P., and Lester, J. N. (2005). Evaluation of environmental burdens associated with sewage treatment processes using life cycle assessment techniques. *Environmental Technology*, 26(3), 231-249.
- [4] Doka, G. (2003). Part IV - Chapter 4: Life Cycle Inventory of Wastewater Treatment. In: *Life Cycle Inventories of Waste Treatment Services - Ecoinvent Report No.13*, Swiss Centre for Life Cycle Inventories, Dubendorf, Switzerland.
- [5] Centre for Design. (2004). *Australian LCA Database*. RMIT, Melbourne, Australia.
- [6] Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., and Rosenbaum, R. (2003). IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *International Journal of Life Cycle Assessment*, 8(6), 234.
- [7] Karrman, E., and Jonsson, H. (2001). Including Oxidisation of Ammonia in the Eutrophication Impact Category. *International Journal of Life Cycle Assessment*, 6(1), 29-33.
- [8] Huijbregts, M. A. J., and Seppala, J. (2001). Life Cycle Impact Assessment of Pollutants Causing Aquatic Eutrophication. *International Journal of Life Cycle Assessment*, 6(6), 339-343.
- [9] Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G., and Solomon, S. (2001). Radiative Forcing of Climate Change. In: *Climate Change 2001: The Scientific Basis*, J. T. Houghton and Y. Ding (ed.), Intergovernmental Panel on Climate Change, Cambridge, United Kingdom.