

EVALUATION OF UPGRADE EFFECTS IN FOUR SEWAGE TREATMENT PLANTS IN NSW

ANALYSING THE CONSEQUENCES OF QUALITATIVE AND QUANTITATIVE UPGRADES IN SEWAGE TREATMENT

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ABSTRACT

Significant investment has been made in upgrading municipal sewage treatment plants (STPs) in New South Wales (NSW). This study considers only nitrogen and phosphorus abatement. Out of 10 datasets submitted by the participating municipal councils, four constituting a representative sample of these STPs were analysed, comparing nitrogen and phosphorus concentrations before and after. The upgrades had no significant effect on nitrogen concentration. Phosphorus concentration was significantly reduced in three of the four plants after the upgrade. A cost curve was constructed comparing operation, maintenance and management (OMA) costs with plant capacity equivalent population (EP). Scale economy was found, as OMA cost tends to reduce for every additional unit of plant capacity. Multiple recommendations regarding data collection methodologies and upgrade criteria are given in this article.

Keywords: Cost-efficient nutrient abatement, eutrophication, environmental externalities, hidden cost.

INTRODUCTION

Although sewer systems have been used since the time of the Roman empire (Hvitved-Jacobsen, 2002), it was not until the 20th century that sewage was treated before

discharging it to fresh or marine water systems. The most common negative environmental impacts of untreated sewage discharges on rivers and freshwater streams are: bacterial contamination, odours, dissolved oxygen depletion, eutrophication and fish kills (Hvitved-Jacobsen, 2002; Carpenter *et al.*, 1998).

Freshwater contamination with phosphorus and nitrogen has increased dramatically during the last half-century as a consequence of the intensification of animal and crop production systems. The most common problems associated with phosphorus in freshwater systems are: fish death, unpalatability of water, eutrophication and the formation of carcinogens during water chlorination (Sharpley *et al.*, 2009; Carpenter *et al.*, 1998; Azad and Ancev, 2010; SCA, 2012). Eutrophication is a particularly difficult problem to manage because of its multiple consequences. Some of the most commonly reported concerns are: growth of algae and aquatic weeds that interfere with water for fisheries, recreation, industry, agriculture and drinking, oxygen shortages caused by senescence and decomposition of the algae, and biodiversity loss (Carpenter *et al.*, 1998).

Agricultural practices cause many of the eutrophication issues globally (Mehaffey *et al.*, 2005; Lenat and Crawford, 1994; Azad and Ancev, 2010) and eutrophication is a global problem, as Xepapadeas points out in his review: "54% of the lakes in Asia are eutrophic, 53% in Europe, 48% in North America, 41% in South America and 28% in Africa" (Xepapadeas, 2011). A current focus is finding ways of reducing nutrient loads in both freshwater and marine ecosystems. Laukkanen and Huhtala (2007) found significant economic benefits from reducing eutrophication in such water sources. Consequently, these findings are relevant for economic policy-makers and governments worldwide.

Algal blooms, surface hypoxia, and benthic anoxia are the most common environmental problems caused by sewage emissions of nutrient pollutants. These issues, reported in the literature as point-source pollution, arise as a consequence of elevated levels of organic matter in sewage (Renzetti and Kushner, 2004; Xu *et al.*, 2011; Renzetti, 1999). Nitrogen and phosphorus can be removed from wastewater by means of either chemical, physical or biological treatments (or a combination of them), such as ion exchange, reverse osmosis, ammonia stripping,



Sludge pond at Plant 5 STP.

chemical denitrification, chemical precipitation, biological denitrification and assimilation (Henze *et al.*, 2002). By removing nitrogen and phosphorus from sewage, the above-mentioned environmental impacts can be significantly reduced or even completely avoided, depending on the treatment.

Water reuse has been shown to be an efficient approach to sustainable water management. Multiple authors have based their research on empirical methods of enhancing performance by integrating the water cycle (Sala-Garrido *et al.*, 2012; Lim *et al.*, 2010; Rogers *et al.*, 1998; Alwi *et al.*, 2008). A simplified schematic model of both linear and integrated water cycles is shown in Figure 1. If an integrated water cycle is to be adopted, stringent water quality standards will be demanded as a measure to reduce health issues for the final consumers (Lim *et al.*, 2010). Therefore, it is a requirement to find the optimum point where cost efficiency meets with efficient nutrient removal.

Cost calculations for wastewater treatment facilities have been a favourite research subject for both economists and engineers. However, there is a large gap in the academic literature on the environmental costs for untreated or undertreated sewage discharges into the environment (Renzetti and Kushner, 2004; Laukkanen and Huhtala, 2007; Renzetti, 1999; Hanke and Wentworth, 1981). In addition to the previously mentioned environmental externalities, economic externalities (such as upstream diversion of water or release of pollution on downstream users) and opportunity cost are also factors that

fail to be included in sewage treatment plant (STP) cost evaluations (Figure 2). In this work, the sum of economic externalities, environmental externalities and opportunity cost is referred to as hidden cost.

As a consequence of this hidden cost, water is under-priced. This under-representing of water costs induces both overconsumption of water and sewage discharge, transfers costs to society and places environmental pressures on ecosystems. Additionally, the construction of wastewater treatment

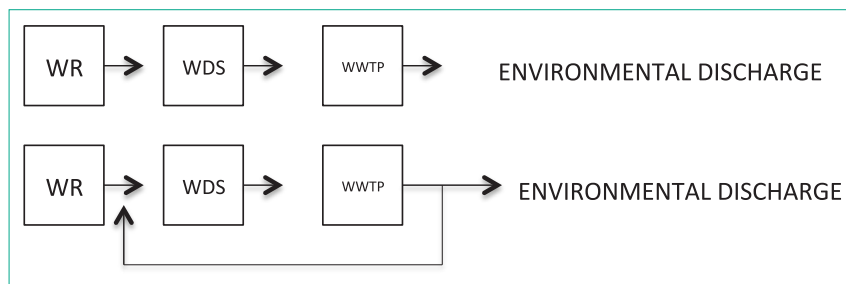


Figure 1. Schematic representation of two different types of water system. Top: a linear or chain water system. Bottom: an integrated water cycle system. WR: water resources; WDS: water demand system; WWTP: wastewater treatment plant. Diagram adapted from (Lim *et al.*, 2010).

facilities implies sunk costs to society that are seldom taken into account. Among others, these five hidden costs to society are to be taken into account when dealing with STPs: reduced value of waterfront dwellings; nitrogen removal costs; reduced recreational and amenity value of water bodies; drinking water treatment costs for removal of algal toxins and decomposition products; and negative ecologic effects on biota (Pretty *et al.*, 2003).

In the Brundtland report, elaborated by the World Commission on Environment and Development in 1987, sustainable development was defined as follows: “*that which meets the needs and aspirations of the present generation without compromising the ability of future generations to meet their own needs*” (Butler and Davies, 2000). Clean water is, of course, a valuable resource for future generations, hence the importance of keeping it as clean as possible. If this definition were to be applied to urban drainage, the technical objectives to follow according to Butler and Davies (2000) would be:

1. Maintenance of an effective public health barrier;

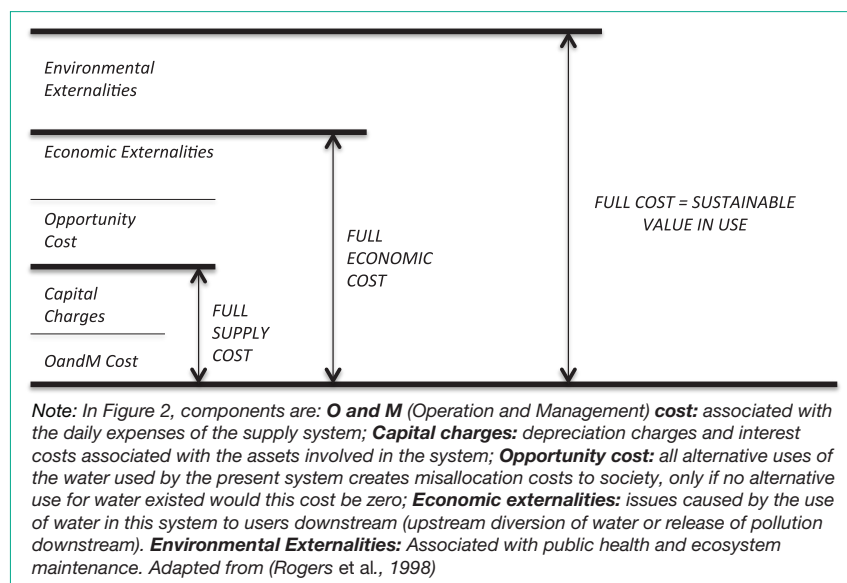


Figure 2. General principles for cost of water.

2. Avoidance of local or distant flooding;
3. Avoidance of local or distant degradation or pollution of the environment;
4. Minimisation of the utilisation of natural resources;
5. Reliability in the long-term and adaptability to future (as yet unknown) requirements.

The aim of this study is to evaluate if: a) STP upgrades have significant effects on nutrient concentrations in effluent; b) a relationship between the size of the STP (taken as equivalent population) and the cost of pollutant abatement exists; and c) the upgrades made have significant effects over operations, management and administrative (OMA) costs in the different STPs.



The main office at the Plant 5 STP.

Table 1. Data received.

Site	Rec (n)	Days	(n) No	(n) Yes	Up (n)	Eff (n)	Down (n)	pH	Cond	OG	BOD	TN	TP	Vol	R
Plant 1	196	26	57	139	1	1	1	1	INC	1	1	1	1	0	0
Plant 2	24	33	2	22	0	1	1	1	0	INC	1	1	1	0	0
Plant 3	15	91	15	0	1	1	1	1	0	INC	1	1	1	0	0
Plant 4	149	28	125	24	0	1	0	1	0	1	1	1	1	1	1
Plant 5	35	30	22	13	0	1	0	1	0	1	1	1	1	1	0
Plant 6	157	15	157	0	0	1	0	1	1					0	0
Plant 7	130	11	130	0	0	1	0	1	INC	1	1	1	1	0	0
Plant 8	79	14	79	0	0	1	0	1	1	1	1	1	1	0	0
Plant 9	131	17	131	0	0	1	0	1	1	1	1	1	1	0	0
Plant 10	94	16	13	81	0	1	0	1	1	1	1	1	1	0	0

Note: Out of 10 STPs, only four (bright green) had enough records for analytical purposes. Plant 2 was rejected because it only had two records before the upgrade; Plant 3, Plant 6, Plant 7, Plant 8 and Plant 9 had no records after the upgrade. In addition, it is evident that each STP had unique criteria for data sampling. **Rec (n)** = Total number of records; **Days** = Mean time between records; **(n) No** = Number of records before upgrade; **(n) Yes** = Number of records after upgrade; **Up** = Upstream; **Eff** = Effluent; **Down** = Downstream; **Cond** = Conductivity; **OG** = Oil & Grease; **BOD** = Biochemical Oxygen Demand; **TN** = Total nitrogen; **TP** = Total phosphorus; **Vol** = Volume; **R** = Rainfall. **1** = data available; **0** = data unavailable; **INC** = Inconsistent (multiple records missing).

METHOD

Effect Of Nutrient Concentration As A Function Of The Upgrade

Data was provided for 10 STPs; these datasets were the result of water quality monitoring of local councils' STPs, which is regulated by the NSW Environmental Protection Agency (EPA). The dataset size and quality was heterogeneous from council to council, which posed limitations on the number of variables that could be used for the present study. Out of 10 datasets only four had enough records for analytical purposes. Most STPs had incomplete datasets, or inconsistencies. Only two variables had good quality data throughout all the datasets (nitrogen and phosphorus concentration) so only these were chosen for the analysis (Table 1).

Upgrade data comes from NSW Benchmarking Reports (NSW Office of Water, 2007; NSW Office of Water, 2009a; NSW Office of Water, 2009b; NSW Office of Water, 2010; NSW Office of Water, 2011; NSW Office of Water, 2013; NSW Office of Water, 2012). Based on this information, a dummy variable was created for the function upgrade (0 = before upgrade, 1 = after upgrade). A generalised least squares (GLS) fitted by restricted maximum likelihood (REML) analysis

was performed in R (R Development Core Team n.d.) (Eq.1). Each of the four STPs was analysed individually by fitting this model to its nutrient concentration data.

$$N_c = S\beta + \varepsilon$$

Given:

$$S = f(U)$$

Where N_c = nutrient concentration (nitrogen, phosphorus), U = upgrade (dummy), S = site. Nutrient concentration was log-transformed to comply with homoscedasticity assumptions in the model, resulting in $\ln N_c$ ($\ln N$, $\ln P$).

Effect Of The Size Of STP On OMA Costs

The 2005 to 2011 NSW benchmarking reports used the following formula to estimate operations, maintenance and administration costs (OMA):

$$OMA = \sum m_e + o_e \frac{1}{S_v \times 10}$$

Given:

$$m_e = a_c + e_c; \text{ and } o_e = (M + O + E + C) + (A + P + S + T)$$

Where m_e = management costs, a_c = administration costs, e_c = engineering and supervision costs, o_e = operation and maintenance costs, M = maintenance, O = operation =

operations, E = energy; C = chemicals, A = mains, P = pumping stations, S = sewage treatment, T = other, and S_v = volume of sewage receiving secondary treatment. Note that the factors within o_e are clustered in two different groups – the first one defining processes and the second, type of assets. EP (equivalent population) values were used as size values in the regression. As structural components of wastewater facilities are designed to meet further population growth, calculations (2) were performed assuming the plant operates at 100% of treatment capacity.

$$OMA_p = \sum_{i=1}^n \frac{OMA_i}{n} \quad (3)$$

Sizes of utilities were retrieved from NSW Benchmarking Reports (2005–2012). A mean cost was calculated using the data from NSW Benchmarking Reports as shown in Equation 1. Table 2 shows a summary of the data used as an input for the linear model applied to analyse the relation between size of the STP and OMA cost. A linear model (first-order equation) was used for the present study, as previous work reported this as a sufficiently powerful tool to expose any scale economy (the concept is treated with further depth in the Results and Discussion section) (Fraas and Munley, 1984; Hanke and Wentworth, 1981; Renzetti, 1999).

RESULTS AND DISCUSSION

The nitrogen concentration in the effluent before the upgrade of each STP was compared to the values after the upgrade and no significant difference was found (Table 3). Although some change should have been observable, the high variability of the measurements and the small

size of the datasets make finding differences difficult.

In contrast, when comparing the concentration of phosphorus in the effluent before the upgrades in each STP with the post-upgrade values, a significant difference was found for Plant 1, Plant 10 and Plant 4. No significant difference could be observed when comparing Plant 5

pre-upgrade values with post-upgrade. According to this, after the upgrade all the STPs (except Plant 5) had a significant reduction in phosphorus concentration (95% confidence interval). A difference is also observed in Figure 3 where the overall effect of upgrades is analysed.

A number of studies have examined the relationship between size and full supply cost (Figure 2) in wastewater treatment plants (Renzetti, 1999). The mentioned relationship has been found to have a trend towards a cost decrease as the size of the sewage treatment plant increases, commonly called a scale economy. First order equations have been used in the past to reveal the relationship between cost and treatment capacity (Sato *et al.*, 2007; Fraas and Munley, 1984) with evidence that no higher-order equations are required to explain the correlation. However, it was observed in the present work that a logarithmic function fitted more accurately to the data.

To understand if there was a relationship between the size of the plant and its OMA costs, both linear and logarithmic regressions were performed (Figures 4 and 5). A negative correlation was found to exist between plant size and OMA cost. Although a tendency can be seen towards a reduction in costs, points five and six (Plant 4 before and after the upgrade respectively) create a distortion on the model. The reason for this is that Plant 4 had a qualitative (addition of IDEA and of alum dosing to remove phosphorus) upgrade, but not a quantitative

Table 2. Mean operation, maintenance and administration costs before and after the upgrades of selected STPs. OMA costs in cents/ kL.

	Upgrade Date	(Upgrade = 0)	(Upgrade = 1)
Plant 1	1/04/2009	183.5	142
Plant 10	1/03/2010	133.2	125.5
Plant 4	1/06/2011	122.3	149.5
Plant 5	1/05/2012	150.2	132

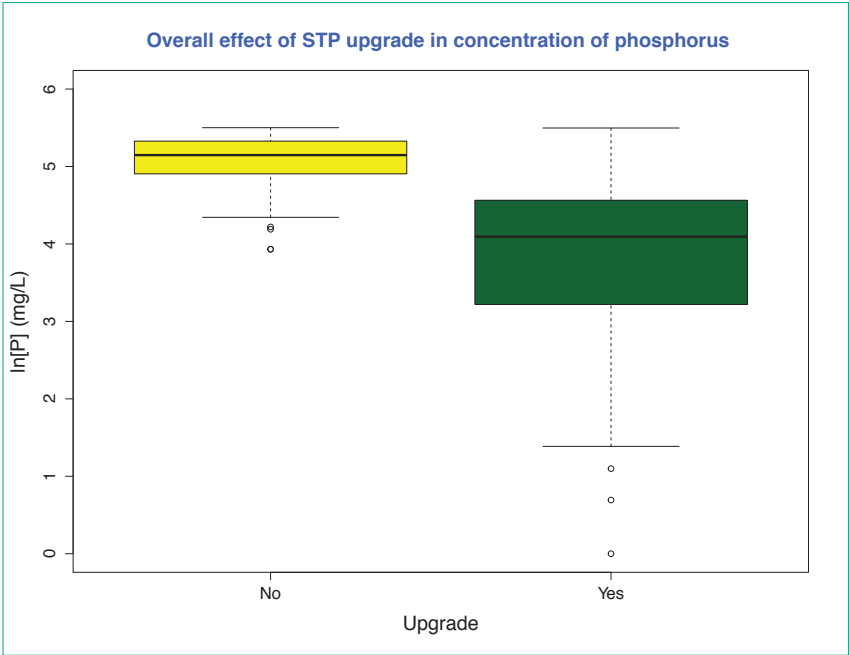


Figure 3. A reduction in the concentration of phosphorus is observed when pre-upgrade effluent is compared with post-upgrade effluent.

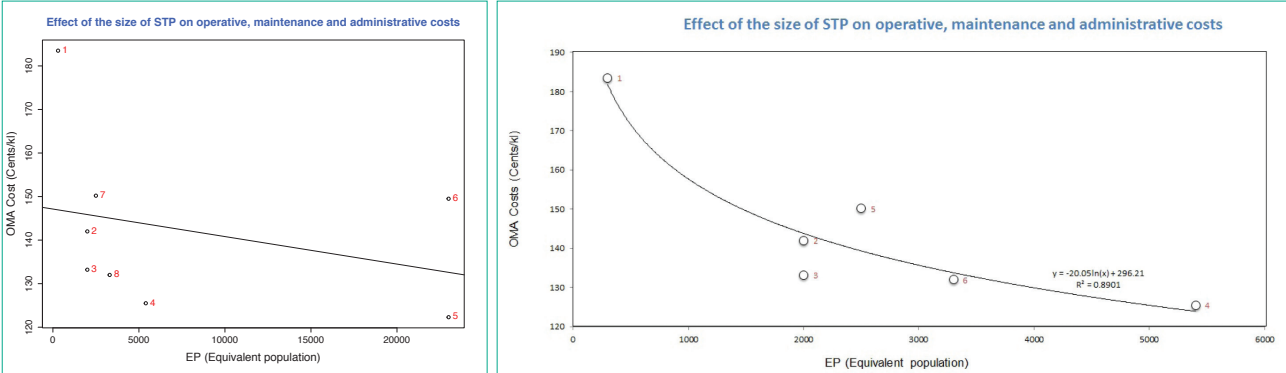


Figure 4. Relationship between the size and the OMA costs for four STPs before and after the upgrade. Left: linear regression ($R^2 = 0.0952$). Right: Logarithmic regression ($R^2 = 0.4441$) (1 = Plant 1 no upgrade; 2 = Plant 1 upgrade; 3 = Plant 10 no upgrade; 4 = Plant 10 upgrade; 5 = Plant 4 no upgrade; 6 = Plant 4 upgrade; 7 = Plant 5 no upgrade; 8 = Plant 5 upgrade).

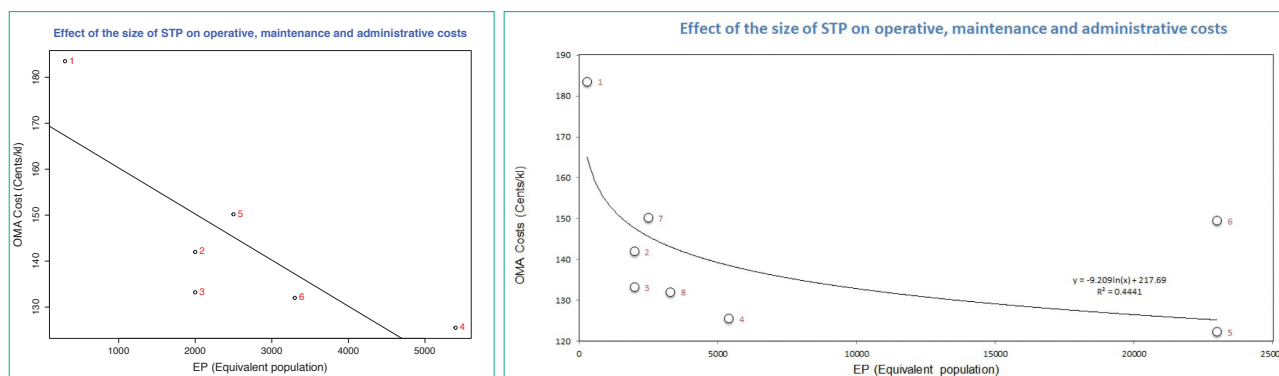


Figure 5. Relationship between the size and the OMA costs for four STPs before and after the upgrade, with both Plant 4 no upgrade and upgrade removed. Left: linear regression ($R^2 = 0.6551$). Right: Logarithmic regression ($R^2 = 0.8901$) (1 = Plant 1 no upgrade; 2 = Plant 1 upgrade; 3 = Plant 10 no upgrade; 4 = Plant 10 upgrade; 5 = Plant 5 no upgrade; 6 = Plant 5 upgrade).

Table 4. Kind of upgrade performed in each of the sewage treatment plants. TF = trickling filter; IDEA = intermittent decanting extended aerator aeration; PC = Pasveer channel; P = phosphorus; EP = equivalent population. Note that there is no quantitative upgrade in Plant 4 STP.

STP	Kind of upgrade	
	Qualitative (treatment used)	Quantitative (EP)
Plant 1	TF replaced with IDEA	300->2000
Plant 10	PC replaced with IDEA	2000->5400
Plant 4	Addition of IDEA	23000->23000
	Addition of alum dosing to remove P	
Plant 5	TF replaced with IDEA	2500->3300
	Addition of alum dosing to remove P	

upgrade (the equivalent population remained 23,000 after the upgrade), as opposed to all other STPs (that had both an upgrade in technology and in treatment capacity) (Table 4). The main issue with this is that although the cost of treating sewage increased due to the increased energy and input requirements of the new technologies,

as a consequence of an increase in cost (without an increase in capacity), no scaling effect can be observed from this facility.

To observe how the difference in the Plant 4 upgrade affected the cost curve, a further analysis was performed: removing Plant 4 both with and without upgrade (Figure 5). It is

clear that when Plant 4 is removed from the logarithmic regression, the regression model has a high explanatory power, showing a clear tendency towards a reduction in cost relative to the STP capacity (EP).

Although management costs showed a decrease when treatment capacity increased, nutrient abatement costs showed different trends. Nitrogen abatement costs did not show any significant reduction in any of the STPs (Figure 6) when compared before (NO) and after (YES) the upgrade.

Phosphorus abatement costs did not show a significant reduction (with the exception of Plant 10 that was reduced significantly after the plant upgrade) (Figure 6). A tendency towards reduction of abatement cost can be seen for phosphorus, but the statistical analysis rejects the significance

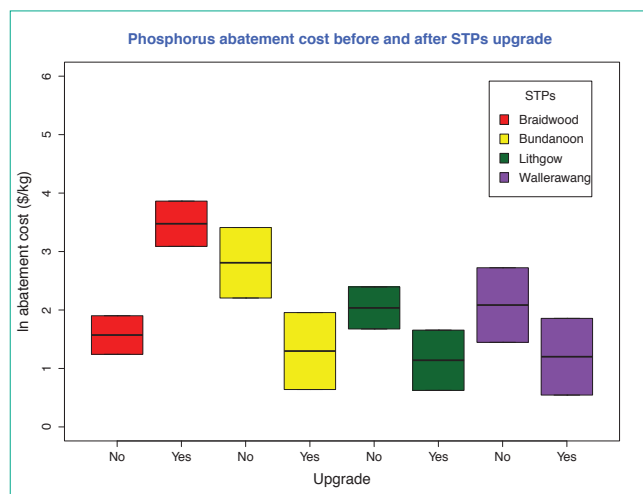


Figure 6. Comparison between the abatement cost of phosphorus in (AUD\$/kg) before and after the STP upgrade.

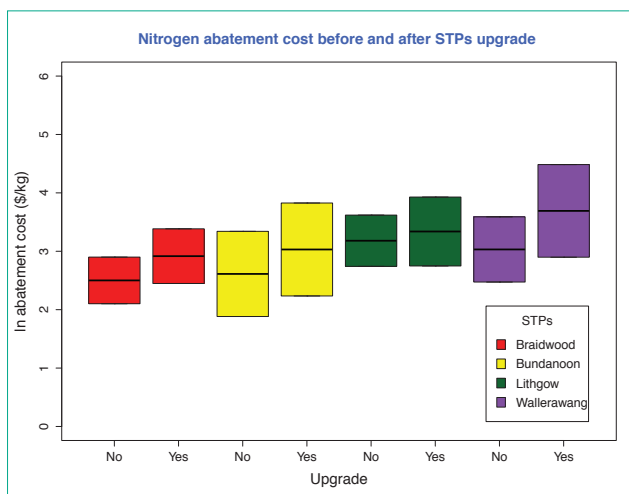


Figure 7. Comparison of the abatement cost of nitrogen in (AUD\$/kg) before and after the STP upgrade.



Solid-free water after exiting the IDEA tank.

of the differences. Reduction in phosphorus concentration was one of the objectives of the upgrade, as a way of controlling phosphorus limited algae populations.

An increase in abatement costs is observed in Plant 1 STP after the upgrade (Figure 6), against what would be expected. No OMA costs were submitted for the years 2005, 2006 and 2007. In order to fill this blank, the averages between years 2004 and 2008 were used as the value for the three missing years. It is highly likely that the actual real (but unreported) data had values higher than our estimates. If this is true, the expected outcome (a decrease in OMA after upgrade) would have been observed as it was with the other STPs.

A major issue throughout the project was the quality of the data. A successful monitoring program depends on good quality datasets, but these were found to be of extremely poor quality (Table 1), with no consistency in monitoring time periodicity (mean periodicity ranged from 11 to 91 days between STPs), lack of monitoring sites' spatial descriptions, and no weather variability annotations (rainfall data was only gathered for one STP). Other valuable indicators such as oil and grease, conductivity and nutrient levels, both upstream and downstream of each specific sewage plant, were not available from most of the councils' datasets. These problems may account for much of the variation seen in the statistical analysis performed in this study, suggesting that, although some



IDEA (intermittently decanted extended aerator) tank, with surface aerator.

changes might be achieved with the implementation of new technology, they may be hidden behind a layer of 'noise', and so, for practical purposes, remain unseen.

A standardised monitoring methodology would guarantee that all STPs follow the same quality guidelines, and provide researchers with standardised data to perform cross-sectional studies. As long as each council enjoys the freedom to take measurements following its own criteria, the heterogeneity between inter-municipal datasets (Table 1) poses serious limitations on the analytical possibilities. Every council should, at least, take all suggested measurements in Table 1 once a month, both upstream and downstream of the plant and also in the effluent.

CONCLUSION

A scale economy is found in the present study, showing a reduction in operation, maintenance and administration costs as the size of the sewage treatment plant increases. This result was expected based on previous studies and follows the rationale behind basic engineering expectations for high-intensity public works. This suggests that upgrades should be performed towards the upper-limit of population size increase, in order to achieve a lower marginal cost (MC) – the higher the EP, the lower the MC.

Nevertheless, it is well known that wastewater treatment facilities are not energy- and input-efficient, making them a low-end sustainable

alternative. As Mark Everard states: restoration and/or conservation of natural resources could be the only way of sustainable investment in catchments (Everard, 2004). As long as damage caused by environmental externalities is not reflected properly in sewage treatment costs (additional to the rest of the hidden cost components), and natural capital and environmental goods and resources fail to be properly valued, it will not be possible to achieve a sustainable use of resources.

Further studies where capital charges, opportunity costs, economic and environmental externalities are included will be very relevant, not only to assess an academic perspective of the costs of water use, but also as a planning strategy tool for public-sector agencies. It will still be difficult to perform this kind of analysis due to the information gap in environmental and ecosystem services values.

Talking about welfare economics, JR Hicks (1939) says: "[...] the aim of economic policy is to maximize the real value of the social income. In order to arrive at such a real value, the quantities of the various commodities produced must be weighted by a given set of prices – and the prices actually selected are those ruling on the market in the actual circumstances considered". Natural resources have to be valued; only when we have placed an economic value on them will we be able to price sewage systems (among other services) correctly in a way that reflects nature's and ecosystem service values.

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