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**Integrating External Costs with Life Cycle Costs of Emissions from Tertiary
Treatment of Municipal Wastewater for Reuse in Cooling Systems**

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Abstract

Tertiary treatment is needed to render secondary-treated municipal wastewater usable in power
plant cooling systems. Various tertiary treatment options exist to provide different levels of water

quality. This paper integrates life cycle inventory emissions from a life cycle assessment approach with direct costs to determine the optimal treatment alternative based on cost-effectiveness and environmental sustainability. The costs of damage due to air emissions released during construction and operation of tertiary treatment alternatives were estimated using a hybrid based approach and were converted to external damage costs. Greenhouse gas emission (CO_2 eq.), acidifying gas emission (SO_2 and NO_x), and particulate matter ($\text{PM}_{2.5}$) emission unit costs were obtained from a Social Carbon Costs study, and cost factors from the Air Pollution Emission Experiments and Policy model were used to determine the total costs of emissions. The sum of average air emissions impact costs for the selected treatment processes were found to be between 5 – 8% of the total costs for tertiary treatment. Accounting for the external air emission costs provides a measure to assess the relative environmental costs of tertiary treatment options for reuse of treated municipal wastewater in cooling systems. Environmental costs of other emissions to air, water and land, as well as benefits stemming from offsetting freshwater withdrawal by reusing treated effluent in power plant cooling systems were not included in the analysis.

1. Introduction

Secondary treated municipal wastewater (MWW) reused as makeup water for cooling systems at thermoelectric power plants has been investigated to reduce withdrawal of freshwater for cooling, and to decrease water contamination and withdrawal-related impacts on aquatic life (Li et al., 2011). Although secondary wastewater is a reliable and easily accessible resource, its higher contaminant concentrations relative to freshwater increase the scaling, corrosion, and bio-

fouling control challenges of managing cooling water quality in recirculating cooling systems (Vidic and Dzombak, 2009). These challenges however can be resolved with advanced treatment of MWW prior to reuse in power plant cooling systems (Li et al., 2011; Vidic and Dzombak, 2009).

Selecting an appropriate level of tertiary treatment of MWW prior to reuse in a recirculating cooling system is an optimization problem. Advanced tertiary treatment processes for industrial water reuse applications are generally chosen based on economic feasibility and effluent quality requirements; rarely is the level of treatment to be imparted decided based on environmental inventory emissions or the economic consequences of those emissions. Construction and operation of advanced or tertiary treatment systems incur not only significant capital and operation and maintenance (O&M) costs, but also lead to consumption of resources such as energy, coal for activated carbon and chemicals, that need to be taken into account when selecting a treatment strategy for MWW reuse (Therregowda et al., 2014).

Extraction of raw materials and production of equipment, chemicals and energy required for tertiary treatment release environmental emissions (such as greenhouse and acidifying gases and particulate matter) that are largely unexamined due to lack of incentives (e.g., credits to reduce consumption of treatment chemicals) to study and quantify these environmental emissions. Previous studies have made efforts to evaluate the net impact of treatment technology created in the pursuit of stringent water quality objectives (Antonucci and Schaumburg, 1975). Tools and/or methods devised to estimate the direct and indirect costs (Hydromantis, 2011), energy and

resource consumption (Racoviceanu et al., 2007; Pasqualino et al, 2010; Tillman, 1998) and air emissions (Stokes and Horvath, 2010; Meneses et al., 2010; Pasqualino et al, 2009 & 2010; Ortiz et al., 2006; Beavis and Lundie, 2003; Bagley, 2000; Roeleveld et al., 1997) associated with wastewater treatment have been developed. These studies have identified energy consumption, chemical manufacturing, sludge handling and disposal to be the main contributors to costs and environmental emissions (Pasqualino et al, 2009).

While there has been some interest in quantifying emissions related to construction and operation of wastewater treatment facilities, previous studies have not made an attempt to integrate the trade-offs and relationships between direct costs and environmental impacts of designs of tertiary treatment processes. For example, negligible tertiary treatment with intensive chemical conditioning can be inexpensive in terms of direct costs as minimal capital cost is required for treatment infrastructure, but the air emissions released due to increased consumption of conditioning chemicals and the impacts on the condenser due to degraded cooling water quality can be high. Neither the internal nor external economic aspects of such design decisions are within the scope of life cycle assessment (LCA) methodology, nor are they addressed by existing LCA tools. Apart from leaving the trade-offs and relationship between life cycle costs (LCC) and LCA uncharacterized, the consequences of separating LCC from LCA are that it limits the influence and relevance of LCA as a decision making tool, and the economic relevance for companies may be missed when cost analyses neglect LCA scope and findings (Norris, 2001).

External costs are the monetized costs imposed on the society, due to direct and indirect damages caused by pollutants emitted during the manufacture of a product or rendering of services, which are not paid by the producers or the consumers nor considered in production or consumption decisions (NRC, 2010). Integration of external environmental and human health costs with economic costs is one approach toward a welfare-based measure of pollution output for any industrial process. One study on the environmental accounting for pollution in the U. S. economy (Muller et al., 2011) showed that the sewage treatment sector had air pollution damages higher than the value added by its service which was because of the lack of means to measure valuable non-market services in the national accounts. Although services for the sewage treatment industry are accounted for by the costs of production such as sewage fees, landfill tipping fees for sludge disposal, and land application costs for biosolids disposal, these fees fail to account for some of the non-market services and impacts, e.g., the external costs resulting from air emissions (Muller et al., 2011). Though this study does not attempt to provide measures for all non-market services and impacts of the tertiary wastewater treatment processes considered, it does make an effort to determine the economic consequence of specific air emissions released during construction and operation of tertiary treatment processes used to treat MWW for reuse in cooling systems. This analysis provided a means of assessing relative environmental impact of the various tertiary treatment options considered.

A total cost assessment tool completed by a collaborative effort of ten multinational companies and the American Institute of Chemical Engineers' Center for Waste Reduction Technologies defined five cost types: 1) direct, 2) indirect, 3) contingent, 4) intangible and 5) external costs

(Norris, 2001). The direct costs include the capital investment, labor, raw material and waste disposal; indirect costs include overhead; contingent costs include fines and penalties, property damage and personnel injury liabilities; intangible costs include difficult to measure costs such as customer loyalty, work wellness, corporate image, union and community relations and; external costs are costs borne by the society (CWRT, 1999).

The objective of this study was to integrate life cycle cost estimates and life cycle inventory emissions calculated for various MWW tertiary treatment options in terms of monetary cost to aid in selection of a cost-effective and environmentally sustainable approach for tertiary treatment of MWW. Total costs in this study integrated the first (direct) and last (external) type of costs among the five cost types described above. After calculating the environmental costs for the air emissions, the costs were adjusted to 2009 U.S.Dollars/m³ (USD/m³) and then added to the life cycle conceptual costs obtained from the life cycle costing (LC³) model estimates. The sum of the above mentioned costs represent the combined direct and external costs of tertiary treatment (in 2009 USD/m³) normalized for a given loading rate of the treatment plant.

The annual external costs due to greenhouse gas emissions (ton CO₂ eq.), acidifying gas emissions (kg SO₂ and kg NO_x) and particulate matter emissions (kg PM_{2.5}) from construction (fabrication of treatment infrastructure and equipment) and operation (energy, chemical and other supplies production) of MWW tertiary treatment alternatives were estimated using a hybrid LCA approach and external unit damage cost factors (in 2010 USD/ton or 2002 USD/kg). The effects of other emissions to air, water and land, as well as benefits stemming from reduced

freshwater withdrawal for cooling systems were not estimated due to lack of established cost factors for those emissions.

2. Methodology

The total cost assessment for construction and operation of tertiary treatment processes involved extraction of life cycle cost (LCC) estimates and life cycle inventory (LCI) emissions from the LCC and LCI analyses performed previously for the various treatment processes considered (Theregowda et al., 2013 & 2014), followed by the determination of cost factors for emissions averaged across the country. The external impact costs were discounted or inflated to the year 2009 and then added to the LCC estimates to obtain the total costs (in 2009 USD/m³).

The secondary and tertiary treated water quality from FTMSA used for design of tertiary treatment units and the MWW tertiary treatment alternatives considered in this study and for which the integration of LCC and LCI was conducted are listed in Table 1 (Vidic and Dzombak 2009; Theregowda et al., 2013) and Table 2 (Theregowda et al., 2013), respectively. Direct use of river water (RW) with filtration as cooling water makeup was also evaluated to provide a benchmark for the tertiary treatment costs. All the tertiary treatment processes considered included addition of chemical conditioners after treatment, with the doses varied based on effluent quality. Benefits and impacts of reusing minimally treated secondary municipal wastewater in the cooling system, and the recommended level of tertiary treatment and dose of chemical conditioners to be applied for suitable reuse in cooling systems have been considered in

choosing the six tertiary treatment alternatives selected for this study (Hsieh et al., 2010; Choudhary et al., 2012; Liu et al., 2012).

The system boundary for this study, shown in Figure 1, included the tertiary treatment units, chemical conditioning agent additions, and transport of treated effluent from the treatment site to the point of reuse. The functional unit was the treatment capacity for which the processes were designed, i.e., 7.75 MGD, the quantity of make-up water required by the recirculating cooling system of a 550 MW pulverized coal-fired power plant (U.S.DOE, 2007).

2.1 LC³ Model Cost Estimates

Life cycle cost estimates (in 2009 USD/m³) were calculated using the LC³ model (Theregowda et al., 2013), a public domain ‘conceptual’ cost model which provides first-stage cost estimates within the conceptual cost estimation accuracy range of 15-40% as defined by International Association for the Advancement of Cost Engineering (Westney, 1997). In the LC³ model, annual-cost estimates are calculated as the sum of the recurring costs (RC), also known as operation and maintenance costs, and the non-recurring costs (NRC), otherwise known as capital costs, and converted to an annual cost basis. For the purpose of this study, NRC estimates include annualized infrastructure construction costs and the costs of pumps, motors, auxiliary mechanical and digital equipment. While using LCC as inputs to the LCI model, NRC estimates were considered to be distributed over the service life of the equipment or treatment plant life commonly assigned, i.e., 25 years for concrete infrastructure, 10 years for pumps and mechanical equipment and 15 years for the digital control equipment. For direct cost estimates, NRC was

considered to be the amortized capital costs with a capital recovery factor of 12% (de Neufville, 1990) over the service life (25 years) of the treatment plant.

2.2 Life Cycle Inventory Emissions

LCI emissions were estimated from annual estimates from the LC³ cost estimating model for individual treatment units along with the quantity of operational chemicals, activated carbon, and energy; these data were used as inputs to economic input-output (EIO-LCA) (CMU, 2012) and a process-based LCA (PRé Consultants, 2008) model to estimate total LCI emissions for the system (Theregowda et al., 2014). The annualized cost estimates from the LC³ model were referenced to 2009 U.S. dollars (USD), but later converted to 2002 USD input for synchronization with the EIO-LCA model (Theregowda et al., 2014).

Inventory of emissions associated with activated carbon, chemicals for treatment and conditioning, energy and delivery distance for chemical transport were obtained from the ecoinvent v2.2, U.S.LCI and Franklin databases summarized in Table 3. The life cycle environmental emissions included in the study inventory were greenhouse gases (GHG), sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM_{2.5}) emissions to the atmosphere. Equivalent GHG emissions (kg CO₂ eq.) were calculated using the IPCC 2007 100a characterization method (IPCC, 2007). Sulfur dioxide (t SO₂), nitrogen oxides (t NO_x) and particulate matter <2.5 micron size (t PM_{2.5}) pollutant emissions were estimated using the output inventory obtained from the U.S.EPA Aerometric Information Retrieval System (AIRS) data

(U.S.EPA 1989 & 1993) in EIO-LCA, and the aforementioned ecoinvent, U.S.LCI and Franklin databases in SimaPro.

2.3 Estimation of External Costs for Emissions

A number of studies have been conducted to try to quantify the environmental impact costs of air emissions. Using data on the social costs of production, attempts have been made to make integrated “green” national accounts by adjusting them for environmental (and other) costs [32](Matthews and Lave, 2000; Nordhaus and Tobin, 1972; Daly and Cobb, 1989). A summary of social cost of carbon (SCC) updated based on the latest peer-reviewed version of the integrated assessment models used to estimate SCC revealed the three 2010 SCC average values (in 2007 USD) to be \$11 (discount rate = 5%), \$32 (discount rate = 3%) and \$51 (discount rate = 2.5%) and the 95th percentile value to be \$89 (discount rate = 3%) (U.S. Government IWG, 2013). The average \$32 (2007 USD)/ton cost was implemented in this study for emissions of CO₂ eq.

For the other air emissions considered in this study, average costs were used from the APEEP (Air Pollution Emission Experiments and Policy) model (Muller and Mendelsohn, 2007). APEEP estimates the marginal (incremental) human health and environmental damages corresponding to marginal emissions of PM_{2.5}, VOC, NO_x, NH₃, and SO₂ on a dollar-per-ton basis at the county level (Muller et al., 2011; U.S.BLS, 2012). APEEP estimates the damages stemming from emissions at nearly 10,000 sources in the contiguous U.S. Damages include adverse effects on human health, reduced yields of agricultural crops and timber, reductions in

visibility, enhanced depreciation of man-made materials, and damages due to lost recreation services. APEEP employs the results from numerous, peer-reviewed studies that apply these methods to value the physical effects of air pollution. It then evaluates emissions at different release heights.

To estimate the mean value of air pollutants, the APEEP model incorporates assumptions which introduce errors to the external cost estimates. Evaluation of these errors was beyond the scope of this study. The assumptions in APEEP include:

- 1) Cost estimates are accounting measures and not measures of economic welfare. The economy has many existing distortions other than those from air pollution—such as taxes, distortions from market power, and other externalities—and existing accounts do not attempt to incorporate those.
- 2) The model includes only the impact of air pollution and excludes other externalities such as those involving water, soil, and radiation.
- 3) The uncertainties in the external cost factors are particularly large for the value of mortality risks, the relationship of this value to age, the mortality effect of fine particulates, and the social cost of CO₂ emissions (Muller et al., 2011).

In this study, APEEP cost estimates of 5.70 USD/kg SO₂, 1.60 USD/kg NO_x and 11.40 USD/kg PM_{2.5} for mid-level point sources (effective height between 250 and 500 meters) were used to assess emissions associated with tertiary treatment of MWW. County based weighted average

APEEP cost factors determined for the U.S. was used for this study (Mashayekh et al., 2011). The external cost estimates were adjusted to the year 2009 based on dollar value inflation (19.3% from 2002 to 2009 and 3.5% from 2007 to 2009) rates (U.S.BLS, 2012).

Due to accounting of spatial variability in the cost factors, the uncertainty introduced to the external costs is estimated to be very high. This uncertainty can be reduced if the spatial location of the input inventory production or use is specified by an approximate regional boundary i.e., rural or urban location and by accounting for the 5th and 9th percentile values for the external costs than the entire range of factors (which can include outliers or higher or lower extremes). To study the rural and urban only differences three alternate scenarios were analyzed as provided in Supplemental Material Appendix A, Figure A-1 to Figure A-3.

2.4 Assumptions

Assumptions made while converting air emissions released during construction and operation of tertiary treatment units to monetary damages were as follows:

- 1) The conventional air emission cost factors were taken as average values across the U.S. since specific locations for the treatment plant and the production of materials for construction and operation of the plant were not provided.
- 2) Emissions were assumed to be released mainly during production of materials required for the treatment process, and so the height for release of emissions was assumed to be mid-level (250-500 meter from the ground) and from point sources.

3) Constructing a constant-price time series would require time series for all cost parameter values and defining price indexes for each of the cost parameters (Muller and Mendelsohn, 2007) which were beyond of the scope of this study. Hence the external cost estimates were inflated to the year 2009 based on dollar value inflation (19.3% from 2002 to 2009 and 3.5% from 2007 to 2009) rates.

4) Emissions on-site at the tertiary treatment plant were assumed to be negligible compared to the emissions released during production of material inputs off-site and hence not considered in this study.

3. Results and Discussion

Prior to evaluation of the integrated direct and external costs of tertiary treatment alternatives, it is useful to examine the variability of the marginal damage cost factors. Such an analysis provides insight into the range of values that can be used to account for the external damage costs with spatial and temporal variation and subjectivity included in measuring the marginal damage due to a given set of inventory emissions.

Table 4 shows the different unit costs of external (or social) damages obtained from the literature (Matthews and Lave, 2000) and the APEEP model [36] for each inventoried air emission in terms of 1992 USD and 2002 USD (except for CO₂ eq. for which 2010 USD values are shown). Figure 2 shows the variation (range for U. S. counties) of cost factors between peer-reviewed studies. Also, from values presented in the Table 4, it may be seen that there is a significant increase in the dollar-per-ton values from 1992 to 2002 for all inventory emissions, which may

be due to inflation in market goods (the loss of which is used to evaluate non-market services) or due to increased awareness in acknowledging the damages caused from air emissions released.

PM_{2.5}, SO₂ and CO₂ eq. emissions values across the country vary widely for mid-level point sources as seen in Figure 2. NO_x emissions show the minimum value to be negative, although its range of variation was relatively small. The average dollar-per-ton cost factors used in this study were close to the 5% percentile costs shown in Figure 2 of the range for all emissions considered here, which is well justified by the literature sources and hence uncertainty analysis was not considered in this study (Mashayekh et al., 2011).

Results of the marginal damage costs and the integrated costs calculated using average dollar-per-ton cost factors are shown in Figures 3 and 4, respectively. The margin bars (indicated with error bars) in Figures 3 and 4 show the range of costs calculated using the maximum and minimum cost factors from peer-reviewed literature. Figure 3 splits the costs for individual emissions per treatment alternative to examine the individual allocation of emissions of the total external costs calculated. The GHGs were primary contributors of impact costs for all alternatives except for MWW_pH, wherein the SO₂ emissions allocated to the manufacture of sulfuric acid was higher than the GHG emissions. MWW_NSF and MWW_NFG have noticeably high marginal external damage costs because of the three-tiered treatment infrastructure, electricity for aeration, addition of moderate conditioning and treatment chemicals, and regeneration of spent carbon. Among the two-tiered treatment alternatives, MWW_NF has lower external costs compared to the MWW_SF, because the latter alternative

requires regular dosing of chemicals during tertiary treatment. RW and MWW_F have lower marginal damage costs since they involve only sand filtration (F) as a tertiary treatment step, followed by addition of higher doses of chemical conditioners, to which a major portion of the existent emissions costs can be allocated.

Among emissions, though PM_{2.5} has high average unit costs, the overall costs of those emissions for the treatment units was estimated to be low because the quantity of PM_{2.5} released is much lower compared to other emissions. On the other hand, though GHGs were relatively emitted in much higher amounts, since their cost factors were not very high, their impact costs remain moderate. But, when the maximum cost factor is used, the external costs range high for GHG and low for the other three pollutants corresponding to the cost factors range listed in Table 4.

Figure 4 illustrates the total annual cost (in 2009 USD/m³) which is the sum of direct and impact related costs of emissions. The average impact costs of GHGs, acidifying gas emissions and particulate matter (<2.5 microns in size) emissions vary between 5.3 – 7.2% of the total annual costs, with higher impact costs for MWW_NSF, followed by MWW_NFG, MWW_SF and then MWW_pH. Considering the maximum unit cost factors that can be used to determine the maximum impact costs as seen in the upper margin of the cost bar (indicated with error bar) in Figure 4, the maximum impact costs would be in the range of 45-70% of the total annual costs, which is almost equal to the direct costs incurred from tertiary treatment alternatives.

4. Conclusions

Integration of external costs of emissions with direct costs of construction and operation for various tertiary treatment alternatives for secondary treated municipal wastewater (MWW) was conducted. Accounting for damages caused by the release of air emissions along with the direct economic costs can help balance the external damage and the value added by a particular service, such as tertiary treatment to provide water that can be reused in power plant cooling. The attempt to account for impact costs due to release of greenhouse gases, acidifying gas emissions and particulate matter emissions in this study provides an aid to selecting a treatment alternative. From a perspective of the total costs incurred from tertiary treatment of MWW for reuse in power plant cooling systems, a treatment alternative can be selected based on both direct costs and environmental impact costs. A cost-benefit analysis could be carried out by analyzing the ratio of the costs vs. benefits which provides a distinct value that represents the total marketable services costs to the total non-marketable services and impacts. To further expand the study with a complete environmental sustainability and cost-benefit analysis, environmental costs from other emissions to air, water and land, as well as benefits stemming from offsetting freshwater withdrawal by reusing treated effluent in power plant cooling systems need to be examined.

The results of this study indicate that three-tiered treatment alternatives such as MWW_NSF and MWW_NFG, with regular chemical addition for treatment and conditioning and/or regeneration for tertiary treatment, tend to increase the impact costs and in turn the overall costs of tertiary treatment, even though their percent contribution to the total annual costs was moderate to low. RW and MWW_F alternatives with a single level of tertiary treatment have lower impact costs, but the contribution of impact costs to overall annual costs is higher than all other treatment

alternatives, indicating that these alternatives were less cost-effective when the impact costs were integrated. MWW_NF and MWW_SF alternatives with two-tiered tertiary treatment have moderate external impact costs with moderate infrastructure and chemical conditioner dosing, which makes them (especially the former alternative) better treatment alternatives from the environmental impact perspective since they contribute to the lowest environmental damage from emissions.

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Figure 1. Flowchart of the study system. System boundary for the life cycle assessment (LCA) evaluation of tertiary treatment units is indicated as a dashed line. Treated effluent delivery from the tertiary treatment plant to the thermoelectric power plant is included (Theregowda et al., 2014).

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Figure 2. Range of marginal damage costs (in 2009 USD/kg for SO₂, NO_x and PM_{2.5}, 2009 USD/ton for CO₂) the U. S. taken from social cost of carbon (SCC) study for greenhouse gases (CO₂ eq.), from APEEP for mid-level pollutants emissions of acidifying gases (SO₂ and NO_x) and particulate matter (PM_{2.5}). Error bars represent 5% and 95% of the damage estimates provided in Table 3.

Figure 3. Estimated environmental costs (in 2009 USD/m³) of individual air emissions for tertiary treatment alternatives. Average external damage costs per t CO₂ eq. = \$32, per kg SO₂ = \$11.20, per kg NO_x = \$2.26 and per kg PM_{2.5} = \$33 were used for estimation of impact costs

Legend: CO₂ eq. damage costs, SO₂ damage costs, NO_x damage costs, PM_{2.5} damage

Note: kgal = kilo gallon, Nitrification (N), Lime Softening (S), pH adjustment (pH), Filtration (F), Chemical management (C) for anti-corrosive agent –Tolytriazole (TTA), anti-scaling agent – Polymaleic Acid (PMA) and biocide – Monochloramine (MCA)

Figure 4. Total annual costs (in 2009 USD/m³) of tertiary treatment alternatives, inclusive of direct and external costs. Average external damage costs per t CO₂ eq. = \$32, per kg SO₂ = \$11.20, per kg NO_x = \$2.26 and per kg PM_{2.5} = \$33 were used for estimation of impact costs

Legend: Construction of treatment infrastructure, Labor and maintenance, Chemical manufacture and transport for treatment, Electricity for operation, Water supply infrastructure and pumping, Raw source water costs, Damage costs, Chemical manufacture and transport for conditioning

Note: 1) The costs presented in the graph are base treatment costs that include nominal charges for the secondary treated wastewater and supply fees for 10 mile delivery distance and additional chemical management, but do not include additional service or taxes. Secondary treated raw municipal wastewater cost was assumed to have a base value of approximately 0.18 USD/kgal and was added to the tertiary treatment costs when comparing total costs with city water (CW) and river water (RW) costs.

2) kgal = kilo gallon, Nitrification (N), Lime Softening (S), pH adjustment (pH), Filtration (F), Chemical management (C) for anti-corrosive agent –Tolytriazole (TTA), anti-scaling agent – Polymaleic Acid (PMA) and biocide – Monochloramine (MCA)

3) Established RW and CW rates were obtained from state or regulatory agencies (Delaware River Basin Commission, 2011. Minnesota Department of Natural Resources, 2011, WMP Advisory Committee – LCRA Raw Water Rates, 2011 and Black & Veatch, 2010).

Table 1. Secondary and tertiary treated water quality from FTMSA used for design of tertiary treatment units (Vidic and Dzombak 2009; Theregowda et al., 2013)

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Parameters (mg/L unless noted)	Secondary	Tertiary
Calcium (Ca)	41.5	39.7
Magnesium (Mg)	10.7	9.8
Manganese (Mn)	0.32	0.34
Ammonia-N (NH ₃ -N)	21.0	ND*
Nitrate (NO ₃ -N)	3.6	18.1
Total Phosphorus	4.5	3.8
HCO ₃ Alkalinity (mg/L as CaCO ₃)	177.0	25.4
Total Alkalinity (mg/L as CaCO ₃)	177.0	25.4
Biochemical Oxygen Demand (BOD)	31.9	5.8
Total Organic Carbon (TOC)	27.0	8.7
Total Dissolved Solids (TDS)	661	473
Total Suspended Solids (TSS)	40.7	20.8
Specific Conductivity (SC) (mS/cm)	1030	739
pH	7.2	6.8
Turbidity (NTU)	16.7	6.2
Total Coliform (No./100 mL)	10 ⁶ -10 ⁵	10 ⁴ -10 ⁵

*ND – Not Detectable

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24 **Table 2.** List of tertiary treatment alternatives considered for use with secondary treated municipal wastewater (MWW) (Therregowda et al., 2013)

Abbreviations	Tertiary Treatment Processes Included
RW	River water pumped from source and filtered
MWW_F	Filtration (F) only with addition of chemical conditioning agents
MWW_NF	Nitrification (N) and filtration (F) with addition of chemical conditioning agents
MWW_SF	Softening (S) and filtration (F) with addition of chemical conditioning agents
MWW_NSF	Nitrification (N), Softening (S) and filtration (F) with addition of chemical conditioning agents
MWW_NFG	Nitrification (N), filtration (F) and granular activated carbon (G) treatment with addition of chemical conditioning agents
MWW_pH	pH adjustment (pH) with addition of chemical conditioning agents
WSI&D	Treated water delivery infrastructure (pipeline and pumps) and energy to pump water to an average 10 mile distance between POTW and TPP
CW	City water which has been treated for commercial and/or industrial use

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Table 3. Input to the EIO and process-based LCA models to determine the inventory emissions

39 (Theregowda et al., 2014)

Input Parameter	Database/Model used for Inventory
Construction of infrastructure (in 2002 million USD)	EIO-LCA
Pump and pumping material manufacturing (in 2002 million USD)	EIO-LCA
Plumbing fixture fitting (in 2002 million USD)	EIO-LCA
Valve and fittings other than plumbing (in 2002 million USD)	EIO-LCA
Fabricated pipe and other pipe fitting manufacturing (in 2002 million USD)	EIO-LCA
Material handling/manufacturing equipment (in 2002 million USD)	EIO-LCA
Metal tank, heavy gauge manufacturing (in 2002 million USD)	EIO-LCA
*Electricity grid mix (in kWh)	U.S.LCI, Franklin and Eco-invent
*Transportation via road (in ton-km)	U.S.LCI, Franklin and Eco-invent
*Transportation via rail (in ton-km)	U.S.LCI, Franklin and Eco-invent
Landfill (ton)	Eco-invent
Coal for GAC (kg)	Franklin
Natural gas for GAC preparation (Nm ³)	Eco-invent
Steam for GAC preparation (kg)	Eco-invent
*HCl for GAC preparation (kg)	U.S.LCI and Eco-invent
*Hydrated lime for softening (kg)	U.S.LCI and Eco-invent
*Sulfuric acid (100%) (kg)	U.S.LCI and Eco-invent
*Maleic anhydride for Polymaleic acid preparation (kg)	U.S.LCI and Eco-invent
*Monochloramine (kg)	U.S.LCI and Eco-invent
*Soda ash (kg)	U.S.LCI and Eco-invent
^a Chemical manufacture for TTA (kg)	EIO-LCA

^aAssumed as a general chemical (due to lack of specific data on manufacture process)

*Uncertainty analysis conducted for impacts, using available inventory data from other databases such as

42 ETH-ESU 96, BUWAL250, etc., to avoid process variability and account for influence of the inventory data on environmental profile

Table 4. Unit external (or social) damage estimates (1992, 2002 and 2010 USD) from air

emissions of environmental externalities

Species	Estimated external costs (USD/kg of air emissions)			
	min	median	mean	max
^a CO ₂ eq. (1992 USD/kg)	0.002	0.014	0.013	0.023
^b CO ₂ eq. (2010 USD/kg)	0.001	0.011	0.032	0.105
^a SO ₂ (1992 USD/kg)	0.77	1.8	2	4.7
^c SO ₂ (2002 USD/kg)	1.28	13.4	11.2	114.6
^a NO _x (1992 USD/kg)	0.22	1.06	2.8	9.5
^{*d} NO _x (2002 USD/kg)	-0.8	1.75	2.3	8.6
^a PM ₁₀ (1992 USD/kg)	0.95	2.8	4.3	16.2
^{*d} PM _{2.5} (2002 USD/kg)	1.9	17.9	33	197.1

*Mid-level point source emissions

Data Source: a – Matthews and Lave, 2000; b –U.S. Government IWG, 2013;

c –Muller and Mendelsohn, 2007; d – NRC, 2010