An Optimization Model for Designing a Resilient Eco-Industrial Park Network

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Abstract. With a "pollute now, clean up later" practice, rapid economic growth would be very unsustainable. Eco-Industrial Parks (EIPs) which have been the most widespread manifestations of Industrial Symbiosis under the Industrial Ecology framework may be one of the ways to achieve sustainable development. This study proposes a mathematical model focused on the development of planned EIPs by simultaneously optimizing the economic, environmental, and resiliency objectives of an EIP to address today's more pressing sustainability issues. Incorporating resiliency into the design of EIPs make sure that the EIP is capable of maintaining its function even in the midst of disruptions. Resiliency is considered through the number of connections made available to and from each node which represents the system's vulnerability to failure. In order to identify the importance of considering resiliency into the design of EIP networks, an EIP network will be optimized with and without the resiliency objective, and compared against each other.

Keywords: Eco-Industrial Parks, Industrial Ecology, Industrial Symbiosis, Mathematical Modeling, Resiliency

1. INTRODUCTION

Ever since the Industrial Revolution, different industries have always been focused on mass producing products with little to no concern at all to the environmental impacts that their activities may have caused. Today, climate change is very much real, and may be inevitable if industries continue to degrade the environment by the same degree that their economic activities grow.

In the Brundtland Report presented by the United Nations (1987), sustainable development was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." However, by following a "pollute now, clean up later" practice, rapid economic growth would be very unsustainable (Chiu and Geng, 2004).

One framework that enables the decoupling of environmental impacts from economic growth is Industrial Ecology, which was first coined by Frosch and Gallopoulos (1989). Through Industrial Ecology, industrial systems have the ability to minimize their environmental impacts by imitating material and energy cycles that are naturally occurring in ecological systems (Chiu and Geng, 2004).

Under the Industrial Ecology framework, Industrial Symbiosis is one of the more popular concepts closely associated with sustainable development. Chertow (2000) defines Industrial Symbiosis by saying that it "engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products." Industrial Symbiosis allows participants in an industrial park to work together to achieve a collective benefit that is greater than the sum of all the individual benefits that the same participants would have achieved if they worked alone.

Eco-Industrial Parks (EIPs) are the widest manifestations of Industrial Symbiosis (Boix et al., 2015). EIPs should be designed in such a way that eco-efficiency is maximized. That is, economic benefits are maximized while keeping environmental impacts to a minimum. To date, there have already been numerous implementations of EIP spread across many countries all around the world (Chiu and Geng, 2004; Gibbs and Deutz, 2005; Geng et al., 2010; Zhang et al., 2010).

The achievement of the economic and environmental objectives can prove to be a difficult task. One way is through mathematical modelling and optimization. While most of the earlier optimization studies focused on the minimization of freshwater consumption (Nobel and Allen, 2000; Yoo et al., 2007; Chew et al., 2008), later optimization studies were able to account for the EIP's conflicting objectives through multi-objective optimization (Aviso et al., 2010; Boix et al., 2012). More recently, Tiu and Cruz (in press) had demonstrated the trade-off that exists between the economic and environmental objective functions through a weighted goal programming model.

Currently, all of the EIP optimization studies have focused on optimizing the economic and environmental objectives of an EIP (Boix et al., 2015; Kastner et al., 2015). Maximizing the EIP's eco-efficiency have surely been a step towards sustainable development. However, noticeably absent in current EIP models is their ability to guarantee the continuity of EIPs, which can pose threats to the EIPs ability to maintain its promise of sustainable development.

While EIPs have been proven to bring significant economic and environmental benefits, it also generates within itself a series of problems (Xiao et al., 2012). Even though EIPs are eco-efficient, they can still be vulnerable to unanticipated perturbations (Chopra and Khanna, 2015). Such perturbations may cause existing firms to leave the EIP. When this happens, its previously recipient firms will be forced to source its materials from other participating firms. Once the capacity of the other firms become insufficient to handle the increase in demand due to the exit of a supplying firm, the symbiosis may be exposed to cascading failures which can lead to a significant drop in the environmental performance of the EIP, or the failure of the EIP altogether.

It is expected that the EIP will be exposed to greater risks when there is greater dependence of firms within an EIP (Fleig, 2000). For instance, by optimizing the economic and environmental objective functions alone, the model may provide a network design where bulk of the interplant exchanges are made between the firms and one central firm. In this situation, the success of the EIP is mainly dependent on the central firm. When the central firm leaves the EIP due to unforeseen reasons, there will be no more symbiotic exchanges to take place which may cause the entire EIP to fail. By incorporating resiliency into the design of EIPs, problems such as this can be avoided.

While different authors have defined resiliency differently, all authors agree that it is the ability of the system to absorb changes while still maintaining the system's function (Zhu and Ruth, 2013; Chopra and Khanna, 2014; Benjamin et al., 2015).

Chopra and Khanna (2015) highlights the importance of considering resiliency in EIP design by saying that "the need for developing resilient efficient Industrial Symbiosis networks for improving sustainability is a certainty." This means that resiliency should be an important dimension to be considered when designing EIPs in order to ensure the continuity of EIPs, and to ensure that the network design is done correctly and resiliently the first time around.

A survey of literature shows that resiliency in EIPs is not entirely new concept. Different studies may have proposed several different ways of measuring resiliency in EIPs. However, all current researches in EIP resilience were done on already existing EIPs (Zhu and Ruth, 2013; Chopra and Khanna, 2014; Xiao et al., 2015). To date, there has not yet been any study that attempted to incorporate EIP resiliency into the planning of the design of an EIP. By considering resiliency as part of the design and planning process, the network can be designed to meet the economic and environmental objective functions while still ensuring the continuity of the EIP because of its resilience.

2. PROBLEM STATEMENT

In this study, the EIP system is defined as a set of plants that can act as water sources and/or water sinks as shown in Figure 1. There are n number of plants considered to be included in the EIP with predefined interplant, source, and sink distances. Each plant has the option of setting up connections to the freshwater source (blue arrows), to the wastewater sink (red arrows), or to other participating plants (black arrows).

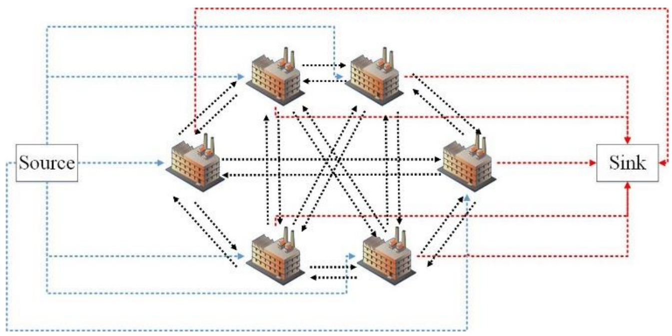

Figure 1: Possible Connections in an EIP

A detailed diagram of the decisions that each participating plant has to make is shown in Figure 2. All plants are assumed to be simple input-output processes that are engaged in a direct integration scheme. In terms of input, each plant has the option of accepting freshwater, untreated interplant water, or treated interplant water as long as the volume and quality combination of these water flows are within the maximum allowable input contaminant concentration. In terms of output, each plant has the option of deciding how much water (with and without) to share with other participating plants in the EIP, and deciding how much water to release to the wastewater sink.

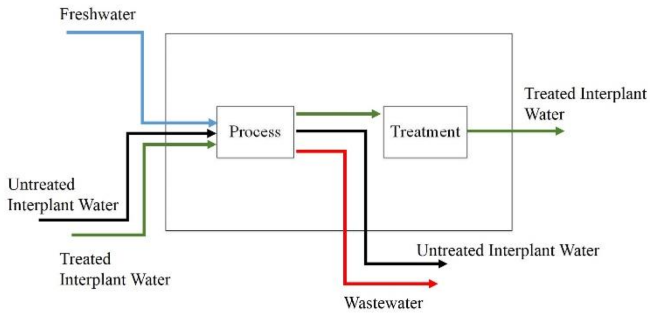

Figure 2: Possible Input and Output Water Flowrates in a Plant

3. MODEL DEVELOPMENT

This study is an extension of Tiu and Cruz (in press). Thus, the indices, parameters, and decision variables used in this Tiu and Cruz (in press) and in this model are the same.

3.1 Sets

N	A set of plants representing participants in the EIP; (1, 2, 3, …, N)
$i(n)$	A subset of plants representing source plants; (1, 2, 3, …, I)
$j(n)$	A subset of plants representing sink plants; (1, 2, 3, …, J)
$c(n)$	A subset of plants representing plant identity number; (1, 2, 3, …, C)

3.2 Parameters

s_i	Available water flowrate in plant i
d_j	Required water flowrate in plant j
$cout_i$	Contaminant concentration of water exiting from plant i
cin_j	Maximum allowable contaminant concentration of water entering plant j
$ctreat$	Contaminant concentration of treated water
$cfresh$	Contaminant concentration of freshwater
pd_{ij}	Distance between plant i and plant j
sd_j	Distance from freshwater source to plant j
dd_i	Distance from wastewater sink to plant i
pc	Cost of constructing pipes
oc	Cost of operating water transfers
tc	Cost of treating water
fc	Cost of extracting freshwater
wc	Cost of disposing wastewater
$cweight$	Weight given to economic goal deviation
$eweight$	Weight given to environmental goal deviation
$rweight$	Weight given to resiliency goal deviation
$xmin$	Minimum economic value of model
$xmax$	Maximum economic value of model
$ymin$	Minimum environmental value of model
$ymax$	Maximum environmental value of model
$zmin$	Minimum resiliency value of model
$zmax$	Maximum resiliency value of model

3.3 System Variables

$Zecon$	Total economic cost incurred by EIP
$Zenvi$	Total environmental impact of EIP
$Zres$	Network degree of centralization of EIP
$Zgoal$	Combination of all objective function deviations to be minimized
$pipe$	Pipe cost incurred by the EIP
$optg$	Operating cost incurred by the EIP
$treat$	Treatment cost incurred by the EIP
$fresh$	Freshwater cost incurred by the EIP
$waste$	Wastewater cost incurred by the EIP
$count_c$	Average number of connections of plant c
$countmax$	Maximum value among all $count_c$

3.4 Decision Variables

A_{ij}	Treated water flowrate from plant i to plant j
E_{ij}	Untreated water flowrate from plant i to plant j

F_j	Freshwater flowrate entering plant j
W_i	Wastewater flowrate generated from plant i
P_{ij}	Binary: 1 if plant i is connected to plant j
Q_j	Binary: 1 if freshwater source is connected to plant j
R_i	Binary: 1 if plant i is connected to wastewater sink
t	Deviation from economic goal
u	Deviation from environmental goal
v	Deviation from resiliency goal

3.5 Objective Functions

The model considers three different objective functions to be optimized simultaneously through the use of goal programming. These objective functions are discussed in the sections that follow.

3.5.1 Economic Objective Function

The total economic cost incurred by the EIP is equal to the sum of a number of cost components as shown in Equation 1. Each cost component can be computed as shown in Equation 2 to Equation 6. It is important that the EIP incur the least cost possible in order to make itself attractive to potential future participants.

$$Zecon = pipe + optg + treat + fresh + waste \qquad (1)$$

$$pipe = \left[\sum_i \sum_j (P_{ij} * pd_{ij}) + \sum_j (Q_j * sd_j) + \sum_i (R_i * dd_i)\right] * pc \qquad (2)$$

$$optg = \left[\sum_i \sum_j (A_{ij} + E_{ij}) + \sum_j F_j + \sum_i W_i\right] * oc \qquad (3)$$

$$treat = \sum_i \sum_j A_{ij} * tc \qquad (4)$$

$$fresh = \sum_j F_j * fc \qquad (5)$$

$$waste = \sum_i W_i * wc \qquad (6)$$

3.5.2 Environmental Objective Function

The total environmental impact generated by the EIP is equal to the difference between the volume and quality combination of the wastewater released by the EIP and the volume and quality combination of the freshwater extracted by the EIP as shown in Equation 7. Volume and water quality combinations of interplant water were not included because they are recycled inside the EIP and is not released into the environment.

$$Zenvi = \sum_i (W_i * cout_i) - \sum_j (F_j * cfresh) \qquad (7)$$

3.5.3 Resiliency Objective Function

The resiliency of the EIP network can be computed by evaluating the network's degree of centralization as shown in Equation 8. This measure was used by Chopra and Khanna (2014) in evaluating an EIP's resiliency. Equation 9 is responsible for counting the number of incoming and outgoing connections to and from every plant in the EIP. Equation 10 compares all the number of incoming and outgoing connections to and from every plant, and takes on the highest value.

$$Zres = \frac{1}{N-2} * \sum_c (countmax - count_c) \qquad (8)$$

$$count_c = \sum_i P_{ic} + \sum_j P_{cj} + Q_c + R_c \qquad (9)$$

$$countmax \geq count_c \qquad \forall c \qquad (10)$$

3.5.4 Goal Objective Function

The goal objective function was used in order to simultaneously optimize the three different objective functions presented. Deviations for each of the three objective functions were obtained through Equation 11 to Equation 13. Finally, the goal objective function was computed as a normalized value of each objective function's deviation multiplied by a weight value given to each objective function as shown in Equation 14.

$$Zecon - t = xmin \quad (11)$$

$$Zenvi - u = ymin \quad (12)$$

$$Zres - v = zmin \quad (13)$$

$$Zgoal = 100 * \left(\frac{t}{xmax - xmin} * cweight + \frac{u}{ymax - ymin} * eweight + \frac{v}{zmax - zmin} * rweight\right) \quad (14)$$

3.6 Constraints

The objective functions were subjected to five groups of constraints as discussed in the sections that follow.

3.6.1 Input and Output Water Balance Constraints

The following constraints ensure that incoming and outgoing water flowrates to and from each plant is preserved. Equation 15 ensures that a plant completely satisfies its demand through accepting interplant water or through extracting freshwater. Equation 16 ensures that a plant completely releases its available water supply either through interplant water or through disposing wastewater.

$$\sum_i (A_{ij} + E_{ij}) + F_j = d_j \qquad \forall j \quad (15)$$

$$\sum_j (A_{ij} + E_{ij}) + W_i = s_i \qquad \forall i \quad (16)$$

3.6.2 Quality Constraint

Equation 17 requires that the sum of all incoming volume and quality combinations of water should be at most equal to the maximum allowable contaminant concentration of any plant. A plant may receive water that may be of poorer quality as long as water flowrates of better quality can offset its effects.

$$F_j * cfresh + \sum_i (E_{ij} * cout_i) + \sum_i (A_{ij} * ctreat) \le d_j * cin_j \qquad \forall j \quad (17)$$

3.6.3 Topological Constraints

Equation 18 to Equation 20 ensures that there should be no treated interplant flow, untreated interplant flow, or even pipe connections from one plant to itself.

$$A_{ij} = 0 \qquad \forall i = j \quad (18)$$

$$E_{ij} = 0 \qquad \forall i = j \quad (19)$$

$$P_{ij} = 0 \qquad \forall i = j \quad (20)$$

3.6.4 Pipe-Flow Relationship Constraints

The following set of constraints describe the relationship between water flows and pipe connections. Equation 21 to Equation 23 ensure that pipe connections must open if there are water flows in the model.

$$A_{ij} + E_{ij} \le M * P_{ij} \qquad \forall i, j \quad (21)$$

$$F_j \le M * Q_j \qquad \forall j \quad (22)$$

$$W_i \le M * R_i \qquad \forall i \quad (23)$$

On the other hand, Equation 24 to Equation 26 ensure that there will be water flows if there are pipe connections in the model.

$$P_{ij} \le A_{ij} + E_{ij} \qquad \forall i, j \quad (24)$$

$$Q_j \le F_j \qquad \forall j \quad (25)$$

$$R_i \le W_i \qquad \forall i \quad (26)$$

These constraints eliminate scenarios where a pipe opens but there are no water flows through the pipe, or where there are water flows but there are no pipes opening.

3.6.5 Connection Constraint

Equation 27 ensures that each plant should have at least one incoming or outgoing connection in order to participate in the EIP.

$$\sum_{i} P_{ic} + \sum_{j} P_{cj} \geq 1 \qquad \forall c \qquad (27)$$

4. RESULTS AND DISCUSSION

The procedure by which the model was optimized is shown in Figure 3. First, the model was solved by minimizing each of the individual objective functions alone, while also computing for the two other objective functions as system variables. The corresponding objective function values were then recorded to the goal parameters (i.e. xmin, xmax, ymin, ymax, zmin, zmax). Second, the model was solved then solved simultaneously through the use of a weighted goal programming objective function.

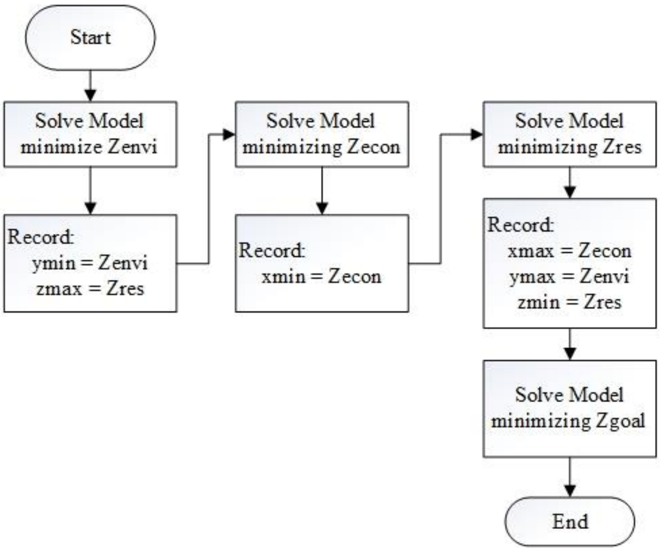

Figure 3: Model Optimization Flowchart

The commercial software GAMS was used to solve the model with the input parameter values as shown in Appendix A to Appendix D. The input parameter values used in this study was obtained from Tiu and Cruz (in press), which was adapted and modified from Aviso et al. (2010).

The optimal EIP network is shown in Figure 5. Blue arrows indicate freshwater connections, while red arrows indicate wastewater connections, and black arrows indicate interplant connections. Interplant connections with values written in black represent the treated interplant flowrates, while values written in red represent the untreated interplant flowrates. The economic cost and environmental impact generated by the EIP, as well as the EIP network's degree of centralization is shown in Table 1.

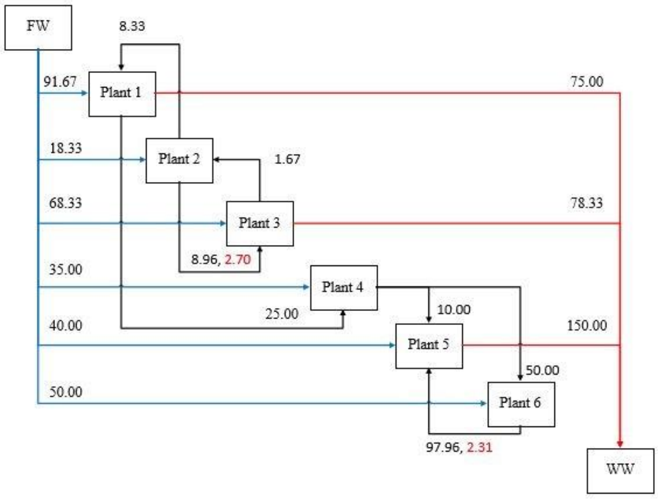

Figure 5: Optimal EIP Network with Resiliency

Table 1: Objective Function Values of Optimal EIP Network with Resiliency

Objective Functions	Value
Zecon	6,167.82
Zenvi	37,883.33
Zres	0.125

In order to show the impact of considering the resiliency objective together with the economic and environmental objectives, the model was optimized again without the resiliency objective resulting to an optimal network as shown in Figure 6.

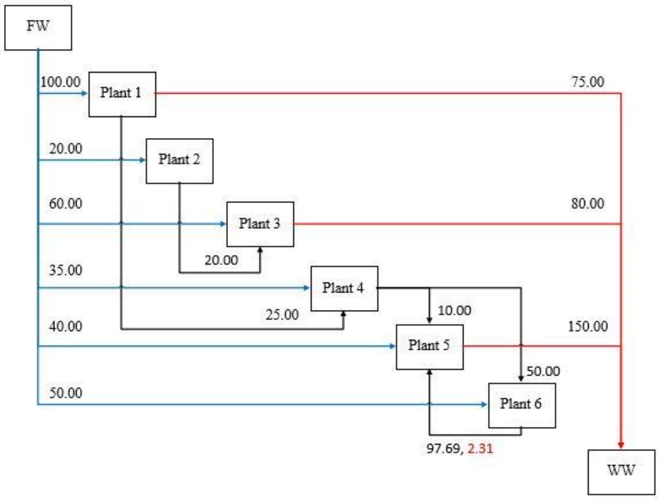

Figure 6: Optimal EIP Network without Resiliency

Table 2 shows a comparison of the objective function values of the EIP network with and without the resiliency objective. While both EIP networks did not vary much in terms of the economic cost and the environmental impact, the resiliency value was 80% lower when resiliency was considered in the model. Given that the resiliency objective must be minimized, a lower resiliency value means a more resilient network – a network that is not dependent on certain central nodes. The resiliency value when resiliency was incorporated was better than when resiliency was not incorporated. This means that the model is able to do come up with an eco-efficient network that is resilient as well. With an 80% decrease in the network's degree of centralization, the network is much more balanced in terms of the number of connections to and from each plant. This will enable the EIP to be resilient and be able to adapt to changes even when unexpected disruptions may arise.

Table 2 Comparison of Objective Function Values of Optimal EIP Networks with and without Resiliency

Objective Functions	Value		Percent Difference
	With Resiliency	Without Resiliency	
Zecon	6,167.82	5,674.54	+8.69%
Zenvi	37,883.33	38,075.00	-0.50%
Zres	0.025	0.125	-80.00%

Table 3 shows the number of incoming and outgoing connections to and from each plant in the two optimal networks. There may be more connections when the resiliency objective was considered but the connections were balanced as compared to when resiliency was not considered. By considering the resiliency objective, the number of plant connections to and from each plant were much more evenly distributed across the EIP as compared to when the resiliency objective is not considered. As such, considering the resiliency objective in designing an EIP network prevents the model from coming up with network designs where majority of the EIP's activities are anchored on a central node.

Table 3: Comparison of Number of Connections of Optimal EIP Networks with and without Resiliency

Plant Number	With Resiliency	Without Resiliency
1	4	3
2	4	2
3	4	3
4	3	3
5	4	4
6	4	3

However, this does not mean that considering the resiliency objective will result to a lower number of connections. In order to make sure that there are no central nodes in the EIP network, the model decided to balance out the number of locations in each connection by opening the same amount of pipe connections in each location.

5. CONCLUSIONS AND RECOMMENDATIONS

While EIPs have been proven to bring significant economic and environmental benefits, it is still vulnerable to unanticipated perturbations which may jeopardize the EIP and incapacitate the EIP's ability to move towards sustainable development. In this study, resiliency was incorporated into the design of EIPs in order to avoid situations that may cause the EIP to fail.

This study incorporated a resiliency objective to the already existing conflicting economic and environmental objectives inherent in the EIP. The objective of the model was to come up with an EIP network design that considers an EIP network's resiliency at the design stage while still considering the EIP's eco-efficiency as well. By considering the resiliency objective, the model was prevented from coming up with EIP network designs where majority of the exchanges loaded on to one central node. The model also showed that it was possible to come up with an EIP network design that is resilient without significantly penalizing the EIP's eco-efficiency performance.

Applying resiliency concepts to EIP network designs is a relatively emerging field, with most of the studies applying resiliency to EIPs on a post-hoc basis. Future areas of research may focus on further improving how resiliency can be applied at the design stage. This may include extending the model from a single period to multiple periods, so that the possibility of pipe degradation or of entering and leaving firms may be incorporated as well.

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APPENDICES

Appendix A. Input and Output Details for Participating Plants

Plant Number	Input		Output	
	Flowrate	Quality	Flowrate	Quality
1	100	10	100	100
2	20	40	20	250
3	80	20	80	80
4	60	30	60	200
5	150	50	150	150
6	100	35	100	130

Appendix B. Interplant Distances

From /To	1	2	3	4	5	6
1	0	150	200	100	175	200
2	150	0	100	100	180	150
3	200	100	0	150	125	200
4	100	100	150	0	100	150
5	175	180	125	100	0	175
6	200	150	200	150	175	0

Appendix C. Source and Sink Distances

Plant Number	Source	Sink
1	100	150
2	50	200
3	150	100
4	200	50
5	125	150
6	180	180

Appendix D. Cost Parameters

Cost Component	Value
Pipe Cost	2.0
Operating Cost	1.5
Freshwater Cost	0.6
Wastewater Cost	1.0