OPTIMIZING RESOURCE RECOVERY IN VANCOUVER

by

Ryan Thoren

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Abstract

Vancouver's expanding population is putting pressure on the city's water and wastewater infrastructure; more efficient uses of this resource need to be explored as the cost of upgrading the city's water and sewer network is daunting. Wastewater presents a significant source of water and heat and, if properly exploited, can reduce pressure on existing infrastructure while reducing stress on the receiving environment. This thesis presents a model with three scenarios that seek to quantify and optimize the amount of water that can be cascaded within the Vancouver Sewerage Area, as well as evaluates each reuse scheme for the economic, environmental, and social benefits associated with each. The first scenario shows a number of potential sources and sinks for direct cascading of wastewater between industries, however water quality represents a significant barrier to this form of water reuse. With the implementation of a satellite water reclamation facility (WRF) in scenario 2, water quality is no longer a barrier and water recycling potential is significantly increased. However, proximity becomes a problem as many of the industries are too far away from the WRF and the cost of pumping and infrastructure far outweighs the benefits of water reuse. When the model is modified in scenario 3 to include the rest of the industrial, commercial, and institutional (ICI) sector and multifamily housing, the potential for water reuse is much greater than the first two scenarios due to the proximity of reclaimed water sinks. The scenario with the greatest water reuse potential, a satellite WRF supplying ICI and multifamily water users, was calculated to recycle upwards of 1,000,000m^3/year. Implementation of this scenario would require up to 50 years to allow for public acceptance, policy implementation, and buy in from government and industry. The required infrastructure is extensive but with proper planning over an appropriate time period, the added benefit of energy recovery from wastewater, and participation from industry and government, water reuse can be a viable option for Vancouver.

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Glossary

Term	Acronym	Definition
Biochemical oxygen demand	BOD	A chemical procedure for determining the amount of dissolved oxygen needed by aerobic organisms in a sample of water to break down organic material present in a given water sample at certain temperature over a specific time period.
Chemical oxygen demand	COD	A commonly used test to measure water quality by indirectly measuring the amount of oxidizeable organic compounds in water.
Code of Practice for the Use of Reclaimed Water	CoP	A companion document to the Municipal Sewage Regulation meant as a key reference and guidance document for the use of reclaimed water in British Columbia.
District energy system	DES	A closed pipe system containing a carrier fluid, usually water or a refrigerant, that caries heat to an end user.
Endocrine disrupting chemicals	EDC	Exogenous substances that interfere with the synthesis, secretion, transport, binding, action, or elimination of natural hormones in the body.
Five day biochemical oxygen demand	BOD_5	A chemical procedure for determining the amount of dissolved oxygen needed by aerobic biological organisms in a sample of water to break down organic material present in a given water sample at certain temperature over 5 days.
Geographic information systems	GIS	A collection of computer hardware, software, and geographic data for capturing, managing, and displaying all forms of geographically referenced information.
Greater Vancouver Water District	GVWD	A legal entity within the Greater Vancouver Regional District to oversee the treatment and distribution of potable water.
Industrial ecology	IE	The study of technological organisms, their use of resources, potential environmental impacts, and the ways in which their interactions with the natural world could be restructured to enable global sustainability.
Linear objective function	LOF	The function to be optimized in a linear programming problem.
Membrane bioreactor	MBR	The combination of a membrane process with a suspended growth bioreactor.

Term	Acronym	Definition
Nephelometric turbidity units	NTU	A standard unit of measure for the turbidity of a liquid
Total dissolved solids	TDS	A measure of the combined content of all inorganic and organic substances contained in a liquid in molecular, ionized or coloidal form.
Total suspended solids	TSS	The dry-weight of particles trapped by a filter, typically of a specified pore size.
Vancouver Sewerage and Drainage District	GVS&DD	A legal entity within the Greater Vancouver Regional District formed in 1914 to oversee the water and sewer networks.
Vancouver Sewerage Area	VSA	Catchment area for the Iona Island wastewater treatment plant that contains Vancouver, the University Endowment Lands, and parts of Richmond and Burnaby.
Water reclamation facility	WRF	A wastewater treatment plant that treats water for the purpose of reuse.

Definitions of Equation Terms

Term	Equation	Definition
ΔQ	1	Change in the heat energy of water.
m	1	Mass of water.
c	1	Specific heat of water.
T	1	Temperature of water.
z	2	Object of be optimized.
c	2	Vector of known coefficients.
x	2	Vector of unknown variable (decision variable).
A	4	Constraint coefficient.
b	4	Vector of constraints.
$Y_{a,b}$	9	Exchange fraction representing the fraction of industry 'a''s inlet water requirement provided by industry 'b'.
I_a	9	Annual volume of water consumed by industry 'a'.
n	9	Index of companies.
$x_{a,b}$	12	Fraction of company 'a''s effluent that it provides to industry 'b'.
O_b	12	Annual volume of sewer discharge by industry 'b'.
E	15	Energy required to pump water per volume of water pumped.
g	15	Gravitation constant.
Δz	15	Change in elevation that water undergoes when pumped.
η	15	Pump efficiency.
f	15	Friction factor of pipe that transports the water.
L	15	Length of pipe.

Term	Equation	Definition
v	15	Velocity of Water
D	15	Diameter of pipe.
ρ	15	Density of water.
EEC	16	Existing electrical consumption required to pump water (i.e. without water sharing)

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Section 1 - Introduction

From 1950 to 2000, the annual fresh water availability per person, as calculated on a global basis, decreased from 16,800 m^3 to 6800 m^3 per year. Current estimations show humans withdrawing 4000 km^3 of water per year, which is roughly 20% of the baseflow of the world's rivers (Shiklomanov, 1997). In light of this increase in global water stress and scarcity, "society no longer has the luxury of using water only once before it re-enters the hydrologic cycle" (Asano et al., 2007). Indeed, over 1.1 billion people lack access to safe drinking water and more than five million people die annually from water-related disease, with these numbers expected to increase as availability of freshwater decreases and the global population increases (WHO, 2004). The United Nations has issued warnings related to an impending global water crisis whereby decreasing water supplies will lead to major health epidemics and international conflicts (World Water Council, 2006). 97.5% of the earth's water is salt water with the remaining 2.5% of fresh water divided in the following ways (World Water Council, 2006):

- 70% is frozen in the polar icecaps
- 30% is present as soil moisture or underground aquifers

Overall, less than 1% of the world's fresh water is readily available for direct human use.

Canada enjoys relatively abundant and high-quality water supplies. Annual precipitation in Canada averages 600 millimetres, although it varies significantly by region (Environmental Canada, 2010). However, 60% of Canada's renewable fresh water drains northward into Hudson Bay and the Arctic Ocean and is thus unavailable to 80% of the Canadian population who live within 100km of the country's southern border (Natural Resources Canada, 2009). Access to this water would require significant infrastructure at prohibitively large monetary and environmental costs.

Effectively, Canada's 'abundant' water supply is more of a myth than a reality. In fact, about 25% of municipalities with water supply systems reported water shortages during 2001, for reasons ranging from source water shortages to treatment and distribution system problems (Environment Canada, 2006). Despite this, Canada is second only to the United States in per capita water use (Pearse & Bocking, 2002). Even within Canada, Vancouver has a relatively high rate of per capita consumption at 542 litres per day in 2007. Of this, residential users account for 295 litres, which is twice as much water use as people who experience similar standards of living in the UK, Germany and the Netherlands (Pearse & Bocking, 2002).

The Vancouver airport receives an average of 1.2m of rain on an annual basis (Environment Canada, 2010). However, the majority of this rain falls during the winter months, leaving the summer months, May to September, comparatively dry. It is not uncommon in this period for the city to experience water shortages. Vancouver's water comes from two of Metro Vancouver's three water reservoirs, Seymour and Capilano. The remaining reservoir, Coquitlam, serves the eastern portions of the lower mainland. The snow pack accumulated during the winter months serves as a source of water during the dryer months as it melts. The recent addition of the Seymour Capilano water filtration plant was implemented to treat the occasional turbid conditions created by rock or mud slides in the reservoir catchment areas.

The plant treats 1.8 billion litres of water on a daily basis to a very high quality, which is then distributed via regional water mains to residences, businesses and industries.

The Seymour Capilano water filtration plant is owned and operated by Metro Vancouver. As of 2010, Metro Vancouver comprises 22 municipalities, one electoral area, and one treaty First Nation. Four separate corporate entities (Greater Vancouver Regional District (GVRD), Greater Vancouver Sewerage and Drainage District (GVS&DD), Greater Vancouver Water District (GVWD) and Metro Vancouver Housing Corporation (MVHC)), operate under Metro Vancouver and representatives from each municipality have a say in how the regions are run. Metro Vancouver and the GVS&DD own, maintain, and operate regional trunk sewers and major wastewater treatment plants, regulate industrial waste discharges, implement required regional actions in its plans, report on plan progress, and collaborate with others as appropriate.

The GVS&DD consists of 4 drainage areas: The Fraser, North Shore, Lulu Island and Vancouver Sewerage Areas (VSA). Covering an area of approximately 13,000ha, the VSA includes the sewer systems of the city of Vancouver, the University Endowment Lands, the University of British Columbia, small portions of the City of Burnaby and Sea Island (City of Richmond). As of March 2008, over 40% of Vancouver has separate sewer systems, whereas the other 60% are combined sewer systems that transport sewage and storm water in a single pipe. Six pump stations are located along the trunk sewers near the northern coastline of the VSA. Wastewater is pumped from the low lying areas in the north to the 8th Avenue interceptor, which runs west until it meets the Highbury Tunnel. From there it runs directly south to the Iona Wastewater Treatment Plant (WWTP). This style of treatment, where wastewater is collected and delivered to a single location, often located away from urban centers, is known as “end-of-pipe” wastewater treatment and has been the standard for the last 150 years.

Located on Iona Island in Richmond, the Iona Wastewater Treatment Plant was built in 1963 and has been expanded six times to accommodate the area’s population growth and treatment upgrades. It treats roughly 600 million litres per day (MLD) from approximately 600,000 people in the VSA at a maximum flow of 17 cubic metres per second. Iona is a chemically enhanced primary treatment plant that utilizes alum and an ionic polymer to help meet biochemical oxygen demand (BOD) standards for periods of dry flow and high influent BOD. Average annual flows to the plant between 1998 and 2007 ranged from 535-617MLD (Metro Vancouver 2007). All primary effluent from Iona WWTP is discharged through a 7.5 km long outfall pipe into the Strait of Georgia. Along with the Lions Gate WWTP in North Vancouver, Iona is one of two remaining primary treatment plants left in Metro Vancouver and is slated to be converted to a secondary treatment plant by 2020 (Metro Vancouver, 2008). BC is far behind all other mainland provinces with only 65.4% of its wastewater receiving secondary level treatment or better, compared to Alberta, Saskatchewan, Manitoba, Ontario, and Quebec which treat 97.0, 97.7, 96.8, 92.3, and 84% of their wastewater to a secondary standard, respectively (Environment Canada, 2006).

With future regional water demand expected to increase by 60% in the next 50 years, Metro Vancouver is trying to determine the full cost of expanding the water supply system in order to compare it to the cost of various water conservation measures (Eco Industrial Solutions, 2004). Within the holistic concept of integrated water resource management, water reuse provides an opportunity to ease the current stresses on water supply, wastewater conveyance treatment and infrastructure caused by increasing water demands, depletion of water sources, reduced supply reliability caused by climate change, ageing infrastructure and limited funding for its expansion (Exall et al., 2004). Water reuse simultaneously promotes environmental sustainability through conservation of water resources and reduces wastewater discharges into potentially sensitive receiving waters. In addition to the economic and environmental benefits associated with water reuse, there also exists the potential for social benefits such as increased partnerships between local governments and businesses, increasing chances for further eco-industrial networks and opportunities for corporations to meet social responsibility objectives (Eco Industrial Solutions et al., 2004). Furthermore, extraction and resale of heat from treated effluent can provide an additional source of revenue and increase economic incentive.

Vancouver purchased almost 130 million cubic meters of high quality potable water in 2005 (GVRD, 2008), a number which many believe to have a large potential for reduction (Friesen, 2008). Reusing water within the VSA will reduce the pressure on the existing water distribution system, sewer collection system and Iona WWTP while reducing the demand for high quality potable water, the need to increase purchased water from outside users, and WWTP effluent discharge into the environment.

A multitude of options exist for water reuse and choosing the optimal methodology requires a great deal of information and planning. A simple form of water reuse can be implemented by using effluent from one water user as another's influent, which can involve very little infrastructure, but is limited to the instances where effluent qualities are cleaner than the required influent qualities. On the other hand, implementing a satellite style treatment plant closer to the points of use can supply significantly more users with a constant flow of treated wastewater, but involves a great deal more infrastructure. Shifting the paradigm in water treatment from centralized WWTPs that utilize "end of pipe" style treatment to using satellite treatment plants can greatly increase the potential for water reuse, bolster public acceptance, pave the way for future water reuse projects, and solidify Vancouver's place as one of the greenest cities in the world.

The goals of this research are to provide Metro Vancouver with an estimation of the water reuse and heat recovery potential within the Vancouver Sewerage Area. This thesis will present the development and results of a model that was designed to identify potential water cascading opportunities among industries. Subsequent modifications of this model include a theoretical satellite water reclamation facility (WRF) to remove the barrier of effluent quality and influent requirements as limitations of water reuse within industry. Finally, the model expands its satellite WRF user base and identifies water reuse potential among industrial-commercial, institutional and multi-family water users, in addition to industrial water users. The results of the model are then analyzed for economic, environmental and social feasibility and are intended to be used as a planning tool to help efficiently and effectively analyze the water reuse and energy recovery options available to Vancouver as the city continues to grow.

Overview and Thesis Structure

Vancouver, for the most part, does not have to worry about water shortages. However, there are a plethora of reasons why Vancouver should look into recovering and reusing this abundant resource.

Decreasing the discharge from Iona WWTP to the receiving environment and reducing the strain on the existing water conveyance infrastructure, thereby delaying or foregoing upgrades to accommodate Vancouver's increasing population base are two major reasons. A computer model developed by Stano (2008) was developed as a tool to quantify the potential for reuse among industries to give government and industry a better sense of the opportunity to use reclaimed water. However, effluent characteristics and influent requirements presented a substantial barrier to large scale water reuse. To address the challenge of water reuse in Vancouver, this thesis presents a modified version of this model that includes a satellite WRF to provide a constant supply of reclaimed water to a larger variety of users. Most of the work done in this thesis was manipulating the model for use in VSA and gathering data to populate the model. The potential for water reuse in the VSA is explored starting in the industrial sector because of its large per connection usage and general acceptance of recycling water. The model then continues into the rest of the industrial, institutional and commercial (ICI) sector and multifamily residences using a theoretical satellite water reclamation facility, which presents a unique opportunity for the recovery and reuse of water within urbanized areas.

The goal of this thesis is to quantify the potential for water reuse in the VSA by means of the modified GIS based optimization model. Before describing the intricacies of the model, this thesis outlines the regulatory framework governing water reuse and permitted sewer discharge, both of which, to a large extent, govern the applications of the model. A literature review is then undertaken to familiarize the reader with the idea of industrial ecology and how water and energy recovery can help achieve more efficient use of resources and to help the VSA grow sustainably. Applications, associated heath concerns, technologies and implementation strategies for water reuse are then discussed. Potable water use in Vancouver is subsequently explored to identify potential areas for reuse within the VSA. Methods and technologies for heat recovery are then presented in the next section. The Following sections provide a brief description of the individual programmes used in the model, namely, geographic information systems (ArcMap), Python, MATLAB and then touches on the concepts behind optimization and linear programming.

Once a background for the model is established, brief formulations of the mathematical optimization functions are discussed in section 4. Section 4 also outlines methods of data acquisition, summarizes the data used in the model and discusses the process of siting a satellite WRF. The results of three different model scenarios are presented in sections 5. A brief, high level discussion of the economics, risk and liability is discussed in section 6, and the economic, environmental and social impacts of a satellite WRF and the triple bottom line benefits or resource recovery and some future avenues of research for the model are presented in section 7. Finally, conclusions of the thesis are presented in section 8. Overall, this thesis aims to not only detail the working of the model and quantify the opportunity for water reuse in the VSA, but also to serve as a guidance document for municipalities considering water reuse by comparing and contrasting the economic, environmental and social benefits of a satellite WRF and direct cascading of wastewater between industries.

Section 2 – Regulatory Framework for Water Reuse in Vancouver

This thesis deals with the recovery of wastewater for purposes of reuse. Thus, two separate regulatory areas must be considered in order to fully address the regulatory guidelines to which projects must adhere. In the first scenario, the model wishes to exploit the 'resource' commonly referred to as industrial wastewater or effluent. Therefore, the wastewater permits will be discussed. Once the wastewater is obtained, it can be cleaned and used again for a specified use. A number of requirements including the level of treatment and the specific uses are outlined in water reuse regulations that are discussed in the following sections.

Waste Discharge Permits

The Iona wastewater treatment plant receives, treats, and discharges an average of approximately 600MLD (Metro Vancouver, 2009) in accordance with the Liquid Waste Management Plan authorized by the Minister of Environment. The majority of this water is from unmonitored sources such as residential properties and storm water runoff. However, a number of industrial point sources have been identified and the primary method used to monitor and regulate the volume and contents of wastewater produced by industrial sources is through waste discharge permits issued under Sewer Use Bylaw 299. The bylaw establishes a permitting framework to allow industrial liquid waste to be discharged to the receiving sewers. Metro Vancouver monitors the liquid waste produced by waste discharge permit holders to determine whether the company's wastewater falls within specified guidelines for volume and the types of contaminants contained. For 2008, the discharge information was calculated based on self-monitoring and sampling data for the period between July 1, 2006 and June 30, 2007.

A permit is required for any commercial or industrial (non-domestic) sewer user that intends to produce liquid wastes on an ongoing basis that:

- contain Restricted Wastes (as defined in Sewer Use Bylaw No. 299); and,
- will be greater than 300 cubic metres within any 30-day period or any instantaneous discharge of Non-Domestic Waste in excess of 30 litres per minute

Industrial sewer users are charged according to how much treatment their wastewater requires and the demands that the wastewater puts upon the sewerage system. The usage charges invoiced to all permit holders in the VSA in 2009 were (Metro Vancouver, 2010):

Biochemical oxygen demand (BOD) – 0.066$/kg;
Total suspended solids (TSS) - 0.623$/kg;
Flow – 0.076$/m^3.

Water Reuse Guidelines

The federal and provincial water reuse guidelines dictate how reclaimed water can be used in Vancouver. They set out minimum standards for different grades of reclaimed water, describe different uses for the water and provide guidelines regarding ancillary structures. They also stipulate allowable discharge volumes and concentrations and the cost of permits allowing sewer users to discharge large quantities of waste, which influences the economics of water reuse. To yield a useful quantification of water reuse potential in the VSA, a water model must act in accordance with all relevant guidelines.

In January 2010 the Canadian Guideline for Household Reclaimed Water became the first Canadian national water reuse guideline. These guidelines are limited to residential toilet and urinal flushing. However interest in reuse applications has grown in regions experiencing water quantity or quality concerns, and both Alberta and British Columbia have each produced guidelines relating to water reuse other than toilet and urinal flushing. The remaining provinces may allow individual reuse projects on an experimental basis, but do not yet have written regulation for routine applications of reuse. In Alberta, wastewater is to be used only for irrigation purposes. The guidelines for wastewater reuse in British Columbia cover a significantly larger range of potential uses. The two main documents that govern the use of recycled water in BC are

Municipal Sewage Regulation under the Waste Management Act; BC Regulation 129/99.

Code of Practice for the Use of Reclaimed Water – A Companion Document to the Municipal Sewage Regulation; Issued May 2001; BC Ministry of the Environment.

The Municipal Sewage Regulation (MSR) gives some basic requirement and very general guidelines on treatment, usage, storage and distribution for recycled water providers and users. The Code of Practice for the Use of Reclaimed Water (CoP) "is intended to be a key reference and guidance document for the use of reclaimed water in British Columbia" and "is designed to support the regulatory requirements prescribed in the MSR" (BC MOE, 2001). The CoP gives relatively detailed descriptions of numerous uses for reclaimed water, references for further information and design considerations for uses such as landscape irrigation, habitat restoration/enhancement and industrial uses. It also provides information on the design, contingency options for excess water, storage, monitoring, labelling and record keeping associated with water reclamation systems.

Schedule 2 of the MSR and the CoP specifically outline the permitted uses and treatment standards for the two types of reclaimed water:

Unrestricted Public Access – Water quality is of a standard that exposure to public presents minimal public health risk and can be used in public areas such as parks, playgrounds, golf courses and toilet flushing

Restricted Public Access – Water Quality is of a lower standard than unrestricted public access and can only be used is controlled areas that do not have unrestricted public access such as agricultural areas, construction sites and wetland areas.

Uses for Unrestricted Grade Water	Required Treatment for Unrestricted Status	Uses for Restricted Grade Water	Required Treatment for Restricted Status
Parks	Secondary Treatment	Industrial	
Residential lawns	Chemical Addition	-Cooling Towers	Secondary Treatment
Vehicle washing	Filtration	-Process Water	Disinfection
Toilet flushing	Disinfection	-Boiler Feed	
Outside fire protection	Emergency Storage	-Stack Scrubbing	

Uses for Unrestricted Grade Water	Required Treatment for Unrestricted Status	Uses for Restricted Grade Water	Required Treatment for Restricted Status
Golf courses		Construction	pH = 6 - 9
School grounds	pH = 6 - 9	-Equipment Washing	$\leq$ 45 mg/L BOD_5
Greenbelts	$\leq$ 10 mg/L BOD_5	-Soil Compaction	$\leq$ 45 mg/L TSS
Building landscaping	$\leq$ 2 NTU (or $\leq$ 5mg/L TSS)	-Dust Control	number of fecal coliform
Street cleaning	number of fecal coliform	-Making Concrete	organisms < 200/100 mL
	organisms < 2.2/100 mL		

Table 1 – A list of selected restricted and unrestricted water uses and their associated treatment and quality requirements. Note that although the treatment for unrestricted water quality states the water must not exceed 2NTU, the MSR also states that a TSS level of 5 mg/L can be used in lieu of turbidity.

In order to plan adequate system size, storage needs must also be considered because although reclaimed water supply is fairly constant, demand for reclaimed water varies through the day and year, particularly for landscape and agricultural irrigation applications. The MSR requires at least 20 days unless the treatment plant has more than one unit capable of meeting the required effluent standards. This may be a good option to implement due to space restrictions and recent research has found a correlation between increasing residence time of reclaimed water and an increase in bacterial growth (Liu et al., 2010), which may increase chlorine costs. Furthermore, emergency storage is required in the event that water quality standards are not met. In addition to proper storage facilities, monitoring of BOD and pH must be done on a weekly basis and turbidity and coliform measurement must be taken on a continuous and daily basis, respectively.

The regulations further stipulate that before the water reuse project begins, a qualified person must conduct an environmental impact study to quantify any environmental damage associated with the usage of recycled water and consent from both the Ministry of Environment and the local health authority (Vancouver Coastal Health) must be obtained. Additionally, uses of reclaimed water that differ from those outlined in schedule 2 of the MSR must be approved in writing by the Director after consultation with the Ministry of Health.

Headway is being made by some provincial governments to develop broad and well rounded policy regarding water reuse, but this undertaking is daunting and there are still a number of hurdles to overcome. A review by The Canadian Water and Wastewater Association (1997) investigated the existence of regulatory barriers to the implementation of on-site water reuse in Canada. The review included health and environmental regulations, plumbing/building codes, and municipal bylaws. It was concluded that there were no absolute regulatory barriers to on-site reuse in Canada. Furthermore, the report noted that the main barriers to implementation across the country are the lack of regulations and guidance, including standardized plumbing codes.

Section 3 - Literature Review

Now that a foundation regarding the federal and provincial guidelines has been established, the literature review section of this thesis aims to give the reader a better understanding of industrial ecology, which is a broad philosophical idea surrounding water reuse and energy recovery from wastewater. With these ideas in mind, a wide range of topics concerning water reuse are explored. The focus becomes narrower when addressing topics that are encountered in this thesis, namely satellite WRFs and water use in Vancouver. Heat recovery is then discussed as the second method by which wastewater can be exploited as a resource. Finally, the computer programs in the model are briefly discussed to give the reader a foundation with which he or she can use to understand the working of this multi-program computer model.

Industrial Ecology

The original intent of the model developed by Stano (2008) was to use water that was initially categorized as waste and turn it into a resource to be used by other companies. This thesis hopes to build on this work and continue along the similar guiding principles of Industrial ecology (IE). Industrial ecology is a system view in which one seeks to optimize the total material life cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal (Graedel & Allenby, 2010). IE is an effective strategy whereby human development can continue to grow economically, culturally, and technologically without compromising sustainability. The concept requires that an industrial system not be viewed as fragmented and in isolation from its surrounding system, but rather within the same shared ecosystem. To be implemented, a movement of thought needs to occur from the idea that there are “natural” areas which are independent from “industrial” area, to the idea that the industrial system is embedded within the natural system (Graedel & Allenby). The idea of IE should not be limited to a company’s property line, but should extend to all impacts on the planet resulting from the presence and actions of human beings.

The idea of IE has gained significant momentum all over the world and there are hundreds of projects in developed and developing countries including Japan, France, Italy, Austria, Finland, Britain, Germany, The Philippines, Thailand, China, and India (Geng, 2004). Canada also has an interest in the idea of IE with preliminary studies being completed in Alberta, Newfoundland, Ontario, and Quebec. Despite implementation in a number of countries, IE, like water reuse, faces a number of challenges before its implementation can be widespread. Institutional, technical, informational, and economic barriers, as well as a lack of available quantifying tools, have all impeded the proliferation of IE (Geng, 2004).

Key concepts regarding IE include conservation of mass and energy and the idea of wasting nothing. By using resources more effectively, businesses save money and can reduce their demand for municipal services, such as water treatment and supply, wastewater treatment, stormwater management, garbage and recycling management, and road construction and maintenance. IE is meant to emulate the ecological aspects of resource cascading in nature because in nature nothing is actually ‘useless’. As such, a wastewater treatment plant that makes use of its effluent should more aptly be called a water reclamation facility and will henceforth be referred to as such. To completely utilize wastes such that an entire eco-industrial network has zero waste is a lofty goal. However, cascading water and the capture of heat energy within the water greatly increases the efficiency of the system and paves the way for further partnership between industries.

This thesis utilizes industrial ecology as a guiding concept. And although IE can be implemented in many more facets of the city, by reclaiming water and heat from wastewater, Vancouver is making more efficient use of its resources and, if properly implemented, will be capable of sustaining a larger population while consuming fewer resources. One of the secondary goals of this thesis is to proliferate the idea of water reuse and resource recovery within an urban setting. By implementing water reuse in non-industrial areas the concept of greater resource efficiency can be more readily spread to the general population and steps can be taken towards public acceptance.

Water Reuse

Past and Current Practices

The idea of recycling water is by no mean a new idea. In fact, some historical records indicate that the use of wastewater in agricultural irrigation was practiced as far back as 3000 years ago (Angelakis, 1999). Beginning around the 16th century, sewage farms were used as a wastewater disposal method in Germany and untreated wastewater was used as irrigation in late 19th century Mexico. Contemporary water reuse involving dual plumbing systems was first seen in the United States in the mid 1920s in Grand Canyon National Park with other arid regions of the United States soon following suit (Asano et al., 2007). Technological developments allowed other water stressed areas of the world to start reusing water. Japan, for example, started reusing treated wastewater in the industrial sector in 1955 and Namibia began direct potable reuse in 1968 (Asano et al., 2007)

Water reuse around the world has seen a rise in implementation due to increasingly severe water shortages. These water shortages are often due to expanding population and the associated increase in food demand, economic development and health issues (O'Connor et al., 2008). Water reuse in the United States began to gain considerable momentum in the 1960s, and this momentum continues today for the following reasons: 1) water shortages 2) significant and rapid population growth in western US and Florida 3) increasingly stringent wastewater treatment and effluent regulations 4) increase in the acceptance of wastewater reclamation and 5) development of appropriate water reclamation and reuse guidelines in many areas (Asano et al., 2007).

As a possible solution to the water shortage, degraded water from sources such as wastewater effluents, stormwater, industrial effluents, irrigation return flows, and gray water can be used to supplement the fresh water supply. Americans alone consume almost 4.8 billion gallons of water daily by flushing toilets and urinals (Division of Pollution Prevention and Environmental Assistance, 2009); it has been estimated that if half of the water from the American municipal wastewater stream was reused in agricultural irrigation, 4 million acres of crops could be produced. The same amount of recycled water would permit the American population to grow by 40% without adding additional strain on current resources (Bastian, 2006). From a global point of view, if half of the world's municipal wastewater was used for agricultural irrigation, 180 million acres of crops could be irrigated, which would be equivalent to supplying 2 billion Americans per year water at their current water consumption rates (Bastian, 2006).

The United Nations Food and Agriculture Organization estimates that approximately 70% of the world's freshwater withdrawals, 820 x 10^7 m^3d^{-1}, are used for irrigation (FAO, 2003). This fact combined with its widespread practice and relatively low water quality requirements, it is easy to see why agricultural irrigation is the largest use of reclaimed water worldwide. Despite being practiced on a large scale for over a half century, significant research is still underway regarding the long term effects of the addition of recycled water to soil. Other uses of recycled water include urban water reuse, aquifer recharge, environmental augmentation, landscape irrigation, and a number of industrial reuse applications. Modern industries have also been reusing water for a number of years where it has provided clear economic benefits.

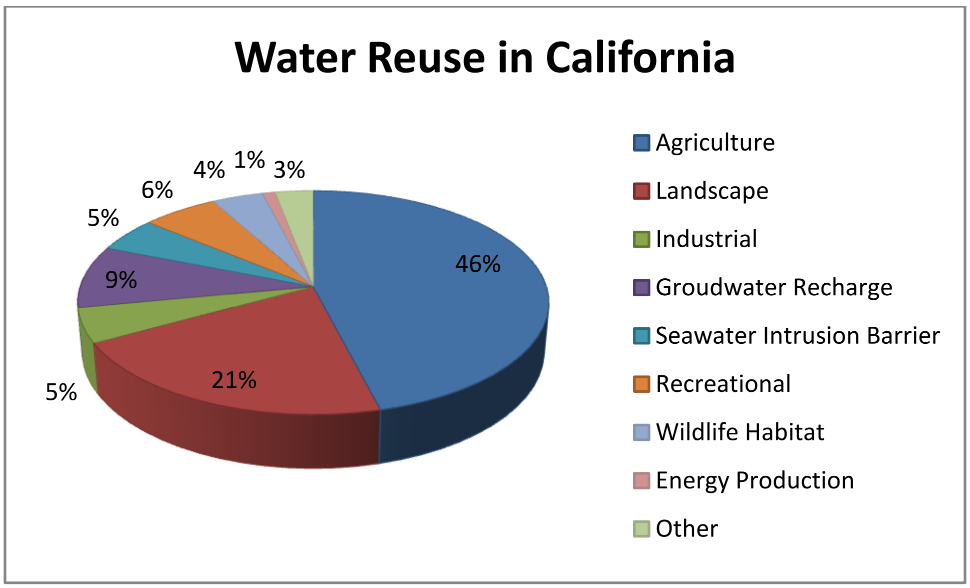

Figure 1 - Breakdown of water reuse in California as percentage of total use Source: Asano et al.

With increasing cost of water associated with stricter treatment and discharge regulations, in addition to growing water scarcity, there has been a shift in sources and uses of water. In 1975 the manufacturing industry did not register any reclaimed water usage, with this number only increasing slightly to 0.4% in 1995. At the same time reliance on groundwater and public water supply increased while the use of saline surface water decreased from 17% in 1975 to 6% in 1995 (Asano et al.). The distribution of fresh water is spread unevenly throughout the world and as a result, the cost of water varies largely depending on geographic and political location. Combined water and wastewater tariffs in Copenhagen, for example, are $8.69/m3; Dublin, on the other hand, does not charge anything for its water and wastewater services (globalwaterintel, 2010). Costs and availability are often the largest incentive for water reclamation (Asano et al., 2007).

It is often an increase in water scarcity or environmental regulation that increases water price, which in turn spurs a movement towards reuse. Other forces that are likely to expand the use of reclaimed water include increasingly stringent discharge standards and health based water quality standards. According to Asano et al. (2007), the four requirements that must be met in order for water reuse to continue to expand are 1) the ability to reliably and consistently meet the new and existing water regulations as well as the demand for recycled water 2) cost effective integration of new technology into existing water treatment and reuse infrastructure, 3) utilization of new water reclamation methods and technology and 4) keeping recycled water economically competitive with other forms of water supply. As urban growth continues, one of the technologies expected to be increasingly utilized is the satellite treatment plant. As the growing metropolitan continues to put pressure on centralized treatment plants, satellite treatment plants will be able increase the volume of available reclaimed water thereby decreasing pressure on existing infrastructure and the impacts of already stressed receiving environments.

Industrial Water Reuse

It is speculated that the decreasing availability of water will increasingly limit industrial processes that utilize it. Water is vital in many parts of industry such as in cooling, cleaning, as a solvent, as a transport medium, and sometimes as a part of the final product. Between 5-20% of global consumptive water use is industry related (Exall, 2004). This number varies largely between countries depending on the level of industrialization. Despite industrial recycle rates of approximately 40% on average, Canadian industry accounts for 80% of water withdrawals (Exall, 2004). Significant benefits with minimal human or environmental ramifications would result from encouraging water recycling in industry and wastewater reclamation and reuse for industrial purposes. Furthermore, with industries often being in proximity to each other and relatively large water usage per connection, the industrial sector can be viewed as the "low hanging fruit" of water reuse because of its relative ease of water reuse implementation.

Water use in the industrial sector is characterized as heterogeneous, highly variable, difficult to adequately categorize, and available to a wide variety of water efficiency measures (Exall, 2004). Resultantly, general methods of recycling and reuse are often difficult to implement. Technical feasibility of industrial effluent reuse was found to depend on a number of factors such as the type of industry, characteristics of the wastewater, the type of treatment system, and the required water quality. When analyzing the economic feasibility of effluent reuse, reuse is usually only implemented when the price of potable water supply and disposal is more than the cost of treatment.

Large water intake and relatively low consumption is typical in the industrial sector and should be recognized as a key statistic when looking at potential for conserving water resources and reducing discharge of industrial effluents into the receiving environment (Exall, 2004). The water quality requirements for industrial water reuse may be determined by process and product quality constraints, and advanced treatment technologies are often required to produce water of acceptable chemical and microbiological quality. General advantages of industrial water recycling are broadly recognized and it is practised where deemed economically feasible, although recycling rates vary widely between industries. In the United States, the use of cooling towers represents the largest use of water in industrial and commercial applications (Division of Pollution Prevention and Environmental Assistance, 2009). A much larger amount, 70-85% globally, is used in agriculture (Graedel et al., 2009). However, industries use water at a relatively constant rate throughout the year as opposed to the seasonal and geographic variations associated with water use in agriculture and landscape irrigation. Resultantly, industries provide a unique opportunity for stable, year-round reuse of reclaimed water (Asano et al., 2007).

A myriad of industrial processes exist with water usage which differs greatly between industry sectors and with life stage. Even within a specific sector such as textile, the extent of recycling varies considerably. It is often the case that the original extraction of resources is particularly water intensive because of the material separation and purification processes involved. Consequently, the non-agricultural sectors with the highest rates of water use are petroleum and coal processing, primary metal extraction, chemical extraction and paper production (Exall, 2004). Furthermore, the materials extraction and processing stage often occurs far from the fabrication of the materials into products, sometimes on another continent. The water used in extraction and processing constitutes a hidden flow effectively invisible to those using the processed material. Furthermore, many types of modern technology often require relatively pure materials, and manufacturing of high purity materials often requires a large amount of water. In general, the water needed to provide materials through recycling is substantially less than that needed if virgin materials are used, so the use of recycled materials is desirable from both a material and a water perspective. (Graedel et al., 2009)

Common industrial users of recycled water are power plants, oil refineries, and manufacturing facilities. The reused water is principally utilized for cooling purposes in once-through or recirculating systems (USEPA, 2004). Many industries employ recirculation of their own process waters for use in areas such as cooling tower make-up water. Defined as the volume of water recirculated as a percentage of total water intake, the recirculation rate varies considerably within the manufacturing sector, from 22% in the wood products group to 292% in plastic products (Scharf *et al.,* 2002). A number of other industries are able to use reclaimed water as process water, but because the recycled water quality requirements can be specific to the industrial process and water application, advanced treatment systems are often required to produce water of acceptable chemical and microbiological quality. To date, industrial use of reclaimed water from municipal wastewater has been limited by cost, water quality, and the availability of reclaimed water. In many cases, the cost of constructing and maintaining reclaimed water conveyance systems is more expansive than using an existing water source (Asano et al., 2007). A workshop held by the Canadian Council of Ministers of the Environment identified the need for policy and economic incentives for industrial water use and a lack of proven technologies as barriers to industrial water reuse in Canada. (Marsalek et al, 2002)

Only a few Canadian policies regarding industrial water use exist, but like most policy regarding reclaimed water, public and environmental health are at the center of concern. The uses for water are extremely varied and precautions should be taken to see that water is treated to a standard that is safe yet useful. There are some typical constituents in recycled water that may render an effluent unusable for reuse and are commonly regulated in policy. The chemicals regularly monitored in water reuse projects can be classified into about half a dozen groups, including biodegradable organics, recalcitrant organics, nutrients, heavy metals, residual chlorine, and suspended solids. The most common parameters for which water quality limits are imposed are BOD, TSS, and total or fecal coliform counts. (USEPA, 2004) The following outlines some of the major constituents of concern in wastewaters.

Oxygen Demand

Oxygen demand, measured as BOD and chemical oxygen demand (COD), is important because it reflects organic content and the associated biological organism growth and the demand for biocides. In general, organics provide food for microorganisms, impact adversely on disinfection, and consume oxygen. Similar to scaling, a biofilm will reduce a heat transfer system's efficiency. Recalcitrant organics resist conventional wastewater treatment and may be toxic in the environment (Selby et al., 1996); their presence may limit the suitability of reclaimed water for some reuse applications. Chlorine may react with waterborne organics and form chlorinated organics, which may be harmful to health. Similarly, major concern for industrial users of reclaimed water is biological stability, which can be affected by the choice of treatment process. Biological problems encountered during industrial reuse and recycling include re-growth of waterborne microbes, biofouling and microbial-induced corrosion.

Suspended Solids (SS)

Total suspended solids (TSS) is one of the most commonly measured parameters in wastewater (USEPA, 2004). Suspended solids are typically made up of silt and clay, microorganisms, and particulate organic matter. This measurement, however, does not provide any information on the particulates in the wastewater in terms of their size, relative density, agglomeration potential, or their settling characteristics. SS provide transport for trace organic constituents and heavy metals, and react with disinfectants thereby reducing disinfection effectiveness. For this reason, SS are often measured directly prior to disinfection. Influent measurements are typical surrogate measures of water quality and provide useful indications of the waste stream's probable physical, chemical, or bio-chemical polluting effects (Andoh, 2004). Monitoring TSS is particularly important in recycled water receiving only secondary treatment because the effluent is not intended to be free of measureable levels of pathogens (Asano et al., 2007). Turbidity is becoming an increasingly popular substitute for SS because it can be measured on a continuous basis as compared to the typical daily sampling for suspended solids. Neither measurement, however, is an indicator of pathogen levels or microbiological quality. Rather, they are used a quality criterion for reclaimed water prior to disinfection.

Ammonia

Ammonia is an important constituent of concern in industrial waters because, firstly, ammonia can be extremely corrosive to copper alloys causing both metal loss and stress corrosion cracking (Selby et al., 1996). This would result in substantially reduced life of certain industrial equipment. Secondly, ammonia is a nutrient for many microorganisms, which can lead to the growth of biofilms or suspended growth of bacterial colonies which can clog machinery.

Phosphate

A major concern with the presence of phosphorus in an industrial setting is the potential for scaling. The exact species that precipitates out depends on the constituents in the water, but the effects of scaling, which results from spontaneous precipitation of phosphorous, can be financially devastating. Struvite, for example, occurs when a system is saturated with respect to magnesium, ammonia and phosphorus. In this situation maintenance costs dramatically increase because of the required acid wash to remove the struvite or, in more extreme cases, the need to replace affected pipes. Other potential precipitates include calcium phosphate and iron phosphate. The potential for calcium phosphate scaling increases with increasing phosphate, calcium, pH, and temperature. Deposits occur particularly at high temperature points such as in a heat exchanger surface and in low flow areas like shell side heat exchangers (Selby et al., 1996).

Phosphorus levels can be chemically controlled to limit or prevent scaling, but a shifting paradigm is beginning to view phosphorus as an increasingly valuable nutrient that needs to be recovered as opposed to removed and disposed of. Phosphorus is an essential element to all living organisms and is often a limiting nutrient in natural systems. Therefore it cannot be discharged into the receiving environment without the risk of eutrophication. Due to its increasingly limited supply, it is now becoming quite economically feasible to precipitate out the phosphorus in a controlled manner and sell it as fertilizer.

Total Dissolved Solids (TDS) and Chlorides

When a water sample is filtered (typically through a 1.5µm filter) and heated to 180°C, TDS are the combined organic and inorganic constituents left on the heating plate. An increase in dissolved solids increases the corrosion reactions by increasing the electrical conductivity of the water. An important dissolved constituent is chloride because it has a particularly strong influence on the corrosion of most metals, especially mild steel, but also for other metals such as copper and stainless steel alloys (Selby et al., 1996). An increase in the chloride concentration will increase the general corrosion, galvanic effects, and potentially pitting corrosion of water.

Examples of Water Reuse in Canada

While worldwide water reuse has rapidly risen to become a worldwide focal point and subject to some of the most heated debates of the 21st century, its spread in Canada is much more limited. Water reuse is most likely to occur in world regions suffering water scarcity, such as in the Middle East, Australia, or the American southwest. Stringent restrictions on wastewater treatment levels is also cause for rapid growth in water reclamation in areas such as Florida, coastal areas of France, Spain and Japan, and densely populated European countries such as England and Germany (Lazarova et al. 2001). In all of the aforementioned areas, the lack of water and severe effluent restrictions promote the economic and environmental conditions that increase the interest and support the implementation of water reuse.

Canadian interest in water reuse first emerged in the late 1970s, when the Canada Mortgage and Housing Corporation (CMHC) sponsored one of the first large-scale Canadian reuse projects (Exall 2004). Conclusions of the study stated that virtually all forms of water reuse, including potable water supply, are technologically feasible. Since then, there have been a number of growing concerns surrounding the identification and treatment of emerging hazardous constituents including endocrine disruptors, pharmaceuticals and personal care products (PCPs). These chemicals have caused headaches for policy makers and WWTP operators alike. Further evaluation of the health effects of emerging chemical as well as the treatment necessary to render them harmless needs to be undertaken.

At present, water reuse is practiced in Canada on a relatively small scale, and mostly in isolated cases (Exall, 2004). Typical examples of such reuse include agricultural cropland irrigation in Vernon, British Columbia and golf course and landscape irrigation as well as industrial facilities in the Prairie Provinces. At 10%, Canada uses far less of its potable water supply for agriculture and landscape irrigation when compared to the global average. Although agricultural irrigation is an accepted and practiced use for reclaimed water, other uses for reclaimed water such as industrial and commercial represent much larger sinks that need to be explored.

Industrial reuse is not a new idea and many industrial operations currently incorporate water recycling measures into plant design, in which effluent is recovered and returned to the process, with the option of treatment beforehand. Millar Western's bleached chemi-thermomechanical pulp mill in Meadow Lake, northwestern Saskatchewan, was built as a zero liquid effluent system with two pressurized rotary screens, flotation clarifiers, settling ponds, and three mechanical vapour recompression evaporators treating the water before recirculation. Some water is lost in process steam and evaporation from storage ponds and some is used in the chemical washing of the evaporator. Nevertheless, the demand for make-up water is only 2 to 2.5m^3per dry metric ton, whereas a typical mill uses 20-25m^3 per dry metric ton (Meadows 1996).

Water reuse can be highly beneficial in rural areas that do not have easy access to potable water. Water distribution systems are virtually nonexistent in some northern parts of Canada and water has to be trucked to the areas and stored on site. In these cases, many communities are considering grey water reuse to reduce the dependence on trucked supply and sewage disposal service. Often rural communities have access to large amounts of land and can utilize waste stabilization ponds for relatively reliable pathogen removal and effluent quality (Exall et al., 2004). However, there are growing concerns that larger volumes of water being recycled results in increased residence time, providing the opportunity for bacterial re-growth that may compromise the initial treated water quality (Liu et al., 2010). The CHMC has supported a number of experimental residential reuse projects that aim to research and showcase new technologies for grey water reuse. A notable example of this is Quayside Village in West Vancouver where a 20 unit apartment complex will treat light and dark grey water by settling, filtration, and disinfection for reuse in toilet flushing.

The practice of reclaimed water irrigation is better established in western Canada as opposed to eastern Canada (Exall et al, 2006). Since 1977, the City of Vernon has operated a water reuse system to utilize its entire effluent disposal by means of irrigating 2,500 acres of agricultural, silvicultural, and recreational lands during the irrigation season from April to October. The city reuses 100% of its effluent and only in emergency cases is effluent discharged into local water bodies. Such effluent irrigation projects must take into account a number of factors such as the end use of the recycled water, nutrient loading on irrigated lands, salinity, and the presence and persistence of pathogens and trace contaminants. The city is planning on spending approximately 100 million dollars by 2015 to upgrade their water infrastructure and treatment (Greater Vernon Water, 2006). The city currently treats its wastewater to unrestricted public access standards and has made attempts to expand the reclaimed water system but has met economic issues and public opposition. (Greater Vernon Water, 2006). Other communities in BC that also reuse water include Osoyoos, Oliver, Penticton, Cranbrook, and Kamloops.

Health and Environmental Concerns Surrounding Water Reuse

Transmission of pathogens is the most widespread concern when dealing with water reuse. The principal infectious agents in untreated municipal wastewater include viruses (comprised of DNA or RNA with a protein coating), bacteria (single-celled organisms), protozoa (also single-celled, but with a distinct membrane-bound nucleus) and helminths (mostly parasitic worms). Until the end of the 19th century, the only illnesses known to be transmitted via water were typhoid fever and cholera (Schoenen, 2002). The current pool of knowledge now consists of a significantly larger list. Some of the most common pathogens include Poliovirus, Norwalk agent and rotavirus. Intestinal parasites commonly found in wastewater include helminthic species such as *Taenia* species (tape worm) and *Ascaris lumbercoides* (round worm), as well as protozoan species such as *Giardia lamblia* and *Cryptosporidium parvum* (Exall et al., 2004). Helminths are the principal cause of human illness and are said to cause 4.5 billion illnesses per year worldwide (Asano et al., 2007). However, helminth infection has decreased significantly in developed countries due to improved sanitary practices and wastewater treatment facilities.

While there has been no epidemiological evidence that recycled water treated to reuse standards has been the cause of disease outbreak in the United States (Asano et al., 2007), the spread of pathogenic organisms from improperly treated wastewater is an issue that impacts both developing countries and industrialized countries. A general vector for the spread of pathogenic material is fecal contamination of drinking water supplies followed by subsequent oral ingestion: so called fecal-oral transmission. Person to person contact and contaminated surfaces and food are also methods of pathogen transmission. Pathogens are also capable of proliferating within inadequately disinfected water distribution systems. Infectious diarrhea is claimed to be responsible for most of the 1.7 million deaths per year (3.1% of all annual deaths) caused by poor water quality, sanitation and hygiene. Of these deaths, 90% are children and virtually all are in developing countries. Moreover, 3.7% of the annual health burden worldwide, which translates to 54.2million disability adjusted life years, is attributed to unsafe water, sanitation and hygiene (Ashbolt, 2004). Problems with drinking water in developing and transition countries are often associated with microbial pollutants, although organic and inorganic chemical pollutants can also play a role (Ashbolt, 2004).

Developed countries are still very much concerned with microbial pollutants as well as organic and inorganic pollutants, particularly in rural areas where less sophisticated water treatment technology is available. Natural waters also contain organic and inorganic constituents. The inorganic constituents are derived from the dissolution of rocks and minerals. The principal inorganic ions are Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, HCO_3^{+}, SO_4^{2-} and Cl^{-}. Other trace inorganic substances will vary depending on the surrounding geology as well as the human and agricultural activities of the region (Asano et al., 2007). The concentration of organic constituents depends largely on the source of the water. Surface waters generally contain far more dissolved organic substances than groundwater, which contains very little, if any organic compounds.

Furthermore, developed countries are faced with problems arising from a number of emerging contaminants of concern such as pharmaceuticals, endocrine disrupting chemicals (EDCs), surfactants, and various industrial additives. A great deal of research is being done to determine the effects of chronic exposure to these emerging contaminants. EDCs have been documented to have a number of adverse health effects on both humans and wildlife (Asano et al., 2007). Many of the emerging contaminants are not yet regulated and do not have established methods for low level detection or removal. Technology and policy are having trouble keeping up with the sheer number of emerging and newly identified pollutants. To date, the European Union list of endocrine disrupting chemicals contains 564 chemicals, of which 147 are thought to persist in the environment (Bolong et al., 2009).

Some of the largest barriers to implementation of large scale water reuse are the concerns surrounding the potential health hazards associated with the use of recycled water. However, regulations in most countries that reuse water are in place for the protection of human health and, if properly implemented, the recycled water does not pose a threat to public health (Asano et al., 2007). Potentially harmful biological contaminants can, for the most part, be treated to safe levels at WWTPs by means of disinfection using chlorine, ozone, or ultra violet light. Future research is still necessary in areas such as removal kinetics, fate, and transport and standard analytical methodology. However, advanced treatment technologies such as activated carbon, advanced oxidation, and reverse osmosis appear feasible for the removal of trace contaminants. Furthermore, it is common practice to implement multiple barriers of treatment to protect against pathogenic material in wastewater.

Technologies and Small Systems for Water Reclamation

Serving the needs of developed and organized societies since the middle of the 19th century (Gikas & Tchobanoglous, 2009), centralized WWTPs are located at low points in drainage areas and receive and treat wastewater from a sewer network that serves the water users of the drainage area. Generally situated away from urbanized areas, water reclamation opportunities from these plants are often limited because of prohibitive storage and distribution costs. Satellite treatment facilities, on the other hand, are small WWTPs built upstream of the centralized WWTP, much closer to the points of reuse. The satellites are connected to sewer infrastructure to extract wastewater and dispose of solids for processing at the central WWTP. The following section discusses technologies and logistics associated with satellite plants.

Costs associated with infrastructure, pumping, and storage of reclaimed water are often prohibitive in the case of centrally located WWTPs. As an alternative to transporting recycled water from centrally located treatment plants, satellite treatment plants treat water for local usage. Depending on the set up of the plant and local constraints, residuals can either be discharged back into the collection system or trucked directly from the satellite facility to a disposal site. The idea of satellite treatment first gained momentum in the early 1960s when the Sanitation District of Los Angeles County (SDLAC) built the Whittier Narrows Water Reclamation Plant for recharge of local ground water. Since then, SDLAC has built a total of seven plants for similar purposes and numerous others in the US have been built to reduce flow to central facilities and/or eliminate or reduce discharges into sensitive receiving water bodies (Asano et al., 2007).

Recent technological advancements have allowed for the production of water of any quality. The main issues in water reuse have now moved on from water quality to reuse opportunities and required infrastructure (Gikas & Tchobanoglous, 2008). Classically, centralized WWTPs have treated all or a portion of effluent from a sewer system in an area far from the wastewater generation sites. With the recent proliferation of water reclamation, the treatment plant can then choose to reuse a portion or all of the effluent, but significant pumping and infrastructure are required to transport the water back to the original point of use. As an alternative to returning reclaimed water from a centralized WWTP, satellite treatment facilities can be built much closer to the source and avoid the expense of long water transportation distances. Satellite WRFs also reduce the volume of raw wastewater flowing through the sewer network, which can allow for increased usage in other parts of the system and may lengthen the time before sewer upgrade or expansion is required.

Furthermore, fecal solids tend to be largest when they first enter the sewage system at the individual household level. They will degrade continually as they encounter different hydraulic regimes, particularly at pump stations where shear forces can be very large. The problem with the continual degradation of solids is twofold: 1) As particles get smaller, they tend to settle more slowly, making it more difficult to separate them from the liquid phase and 2) The breakdown of fecal solids tends to release more of their associated pollutants such as fecal coliforms and heavy metals (Andoh, 2004). It then stands to reason that sedimentation as a treatment process would be much more effective and water quality objectives would be easier to achieve if the wastewater was to be intercepted earlier in the wastewater conveyance system as compared to an end of the pipe treatment.

The location of a treatment plant has a large impact on the size and type of treatment facility, the type of ancillary facilities required, and how a water reuse plan can be implemented. Centralized reclaimed wastewater is widely used for a number of applications such as agricultural irrigation, landscape irrigation, groundwater recharge, industrial uses, and augmentation of recreational impoundments. The potential applications of a centralized WWTP do not differ from that of a satellite style WWTP, but the distribution is often limited to users proximate to the facility. However, volumes of reclaimed water used outside of an urban setting are often large. Agricultural irrigation is the best example of this. In fact, centrally reclaimed water is currently the dominant wastewater reuse source in China and Japan, with the latter sourcing 65.5% of the reused wastewater from centralized WWTPs in 1998 (Chu et al., 2004). The portion of reclaimed water from sources other than centralized water treatment has grown substantially in recent years with an increased interest in satellite, in-house, and on-site wastewater reuse [Bastian, 2006, O'Connor et al., 2008, Chu et al, 2004] due to technological advancements which provide reliable, consistent, and high-quality effluents. A paper by Chu et al., 2004 estimated a total Chinese reclaimed water demand of 327.1 billion cubic meters (BCM), with 93.8%, 4.2%, 0.2% and 1.8% to agricultural, industrial, municipal and domestic water uses, respectively. Due to the constraints on supply and availability for reuse, a maximum supply of only 8.8% of the total demand is currently available from central WWTPs.

A variety of technologies are available to meet the demand for the varying WWTP locations and styles. A proper satellite treatment system is chosen depending on the type of satellite system, demand for reclaimed water, quality of reclaimed water, environmental and site constraints, and compatibility with existing collection systems (Asano et al., 2007). Ideal systems for implementing a satellite treatment approach are those that require minimal or no external sources of power, are simple with no sophisticated controls, are robust and reliable, require virtually no maintenance, and provide effective control at relatively minimal costs (Andoh, 2004). Passive robust devices with no moving parts such as vortex flow controls, advanced hydrodynamic vortex separators, filter systems, and biologically based wastewater treatment systems are all typical examples of treatment and control systems that provide reliable satellite treatment.

Factors such as raw wastewater characteristics, treatment requirements, and odour control issues must be considered when choosing which technologies are implemented. Commonly implemented technologies can be broken down into conventional secondary treatment and compact treatment plants. The conventional secondary treatment includes activated sludge and attached growth, both of which may or may not include nutrient removal depending on the end use of the water. The compact treatment plants include technologies such as membrane bioreactors (MBR) and sequencing batch reactors. Refer to Table 2 for a list of technologies and their associated removals of certain constituents.

Constituent	Unit	Range of Effluent Quality		
		Conventional AS[1] with Filtration	AS with BNR and Filtration	Membrane Bioreactor
Total Suspended Solids	mg/L	2-8	1-4	< 1
Colloidal solids	mg/L	5-20	1-5	0-4
Biochemical oxygen demand (BOD)	mg/L	<5-20	1-5	< 5-10
Chemical oxygen demand (COD)	mg/L	30-70	20-30	< 30-40
Total organic carbon (TOC)	mg/L	15-30	1-5	5-10
Ammonia nitrogen	mg N/L	1-6	1-2	< 1-5
Nitrate nitrogen	mg N/L	20-30	1-10	< 10
Nitrite nitrogen	mg N/L	0 to Trace	0.001-0.1	0 to Trace
Total nitrogen	mg N/L	15-35	2-5	< 10
Total phosphorus	mg P/L	4-8	≤ 2	4-10
Turbidity	NTU	0.5-3	0.3-2	≤ 1
Volatile organic compounds (VOCs)	mg/L	10-40	10-20	10-20
Metals	mg/L	1-1.4	1-1.5	Trace
Surfactants	mg/L	0.5-1.5	10-20	0.1-0.5
Totals dissolved Solids (TDS)	mg/L	500-700	500-700	500-700
Trace constituents	mg/L	5-30	5-30	.5-20
Total Coliforms	No./100 mL	10^3-10^5	10^4-10^5	<100
Protozoan cysts and oocysts	No./100 mL	0-10	0-1	0-1
Viruses	PFU/100 mL	10^1-10^3	10^1-10^3	10^0-10^3

Table 2 - Selected technologies and their associated removal rates. [1] Activated sludge. Adapted from Asano et al., 2007

A growing option for onsite water reuse is the method of decentralized water treatment. Decentralized treatment facilities are very similar to satellite treatment plants in that they are used for reclaiming water from a number of sources such as groups of houses and industries. However, the main difference between the two is that decentralized systems are not connected to the main water collection system and therefore do not have the option of discharging solids back into the sewer system. Decentralized treatment is not included in the model and further discussion regarding these systems will be limited.

In Canada, decentralized wastewater treatment may represent a stepping stone towards water reuse utilizing satellite treatment. Decentralized reclamation is being increasingly implemented, but is still mainly limited to isolated applications and research facilities (Asano et al., 2007). Some applications include individual homes and clusters of homes, isolated industries, service operations, and institutional facilities. In these cases, the most common types of reuse are landscape irrigation and toilet flushing (Exall et al., 2006). Although the reclaimed water is very close to the point of reuse, the volume of water decentralized wastewater facilities can reclaim is relatively small compared to satellite treatment plants because they are independent of the primary sewer collection system. This also limits their ability to buffer the lag between demand of reclaimed water and supply of wastewater. Furthermore, multiple systems may be difficult because knowledge and resources may be limited in more isolated areas and inadequately maintained systems are generally prone to failure. Finally, the solids generated on site have to be periodically trucked out.

By avoiding the spread of many decentralized systems, satellite systems need only to monitor a single treatment process and often only require a single operator. Satellite treatment facilities generally fall into three categories: interception type, extraction type and upstream type. The differences lie in the treatment technologies used and the infrastructure required to implement the treatment facility. Interception type satellite facilities capture the wastewater before it meets the collection system and are most often implemented in high-rise commercial and residential buildings. The extraction type system "mines" wastewater from a collection main or trunk sewer. Upstream type reclamation facilities are located at the extremities of a centralized collection system where opportunities for reuse are available. As urban sprawl continues its migration away from city centres, new developments are often built in sparsely developed land in proximity to golf courses and/or agricultural land. In these cases, an upstream type satellite plant is particularly applicable because reclaimed water piping can be installed at minimal cost. Reclaimed water can be used for golf course or agricultural irrigation and the saving associated with not having to pump the water to a distant WWTP. The proposed satellite WRF in this thesis is an extraction type because it is located directly adjacent a trunk sewer within a highly urbanized area.

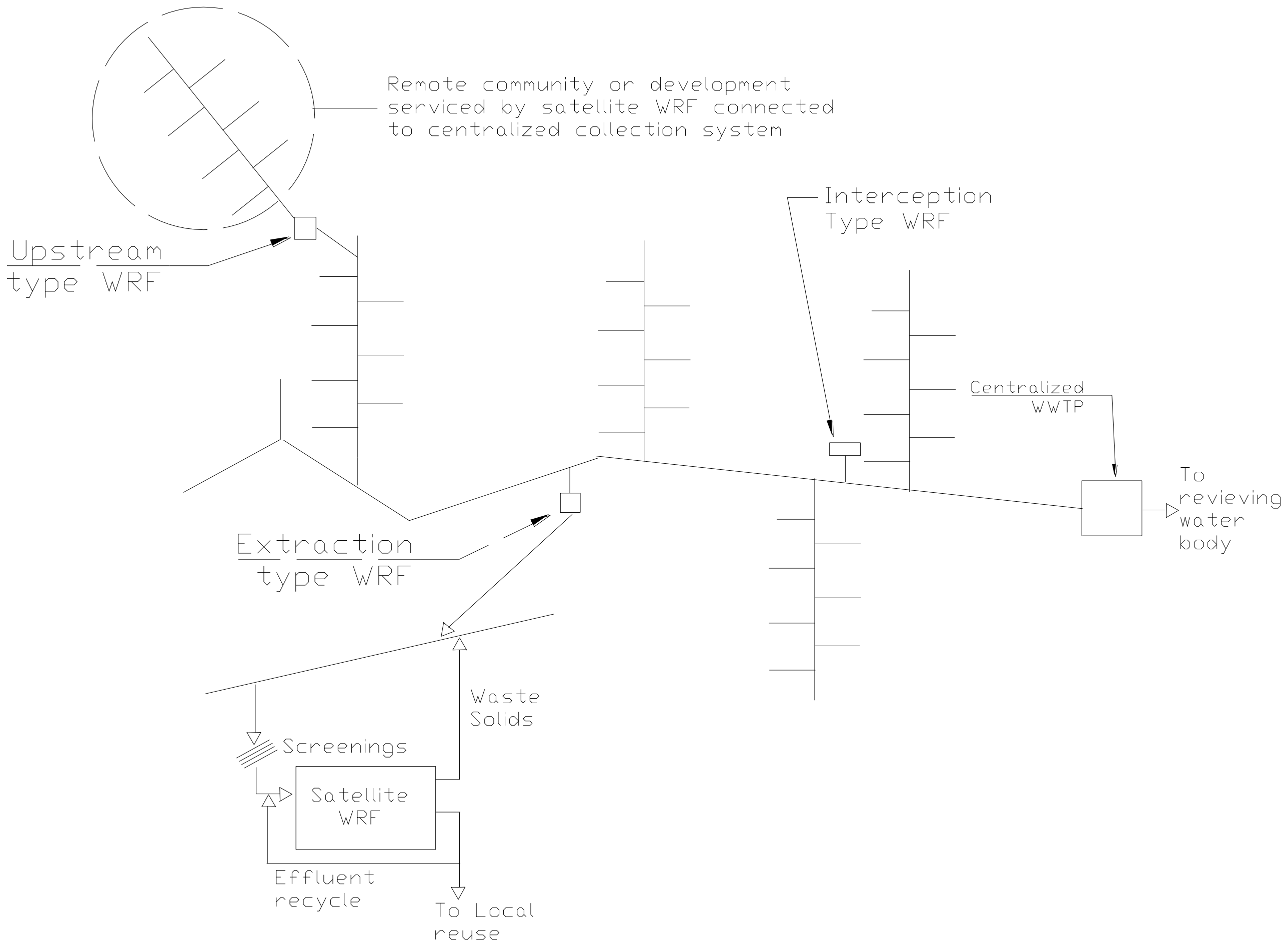

Figure 2 - Illustration of the three different types of satellite treatment plants. Adapted from Gikas and Tchobanoglous (2009).

While the capacity of centralized WWTPs to recycle water is typically limited by storage and distribution costs and decentralized treatment is generally used in small, isolated cases, satellite systems offer proximity to reuse points, relieve pressure to central WWTPs while utilizing existing infrastructure to transport wastewater to users. Due largely to the cost of required infrastructure and levels of public acceptance, satellite systems are not common in urban areas around the world. They have, however, become increasingly utilized in urbanized centers in areas like Japan and the United States. Tokyo, for example, implemented mandatory dual distribution systems in larger buildings in 1984 and began to upgrade three of their centrally located treatment plants to produce water of appropriate quality. As of 1999, over 300 buildings were capable of receiving reclaimed water and as of 2003, 122 buildings were receiving water from one of three satellite style treatment plants (Asano et al., 2007). In short, as water becomes more expensive and as cities continue to expand and increase pressures of water and wastewater infrastructure, satellite treatment facilities will become a more viable option. However, it is not a quick fix and will take years of planning and investment to become a reality.

Challenges in Water Reuse

The previous sections have broadly outlined many of the potential uses and technologies for reclaimed water and touched on some of the setbacks. This section will briefly summarize some of the challenges facing both water reuse and the idea of IE.

This thesis aims to quantify the reuse potential of the VSA as a whole, which is considered very large scale reuse. The immediate drawback of large scale water reuse is the required monetary and planning resources. Large reuse systems like the one presented in this thesis must be implemented over a period of time and be planned in such a way that allows for flexibility in the overall scope, particularly if a number of businesses and industries are involved. This is because a business or industry's lifespan is likely to be shorter than the time frame of a city's water reuse plan. Furthermore, processes and water use within an industry or group of industries may change with evolving technologies and regulatory changes. Implementation of water reuse would likely require a change in policy, and only then would Implementation of the required infrastructure slowly begin to take place. Tokyo, for example, implemented dual piping policy in the late 80's and wasn't reusing water on a large scale for 10-20 years (Asano et al., 2007)

When attempting to cascade water between industries there are a number of barriers that hinder intercompany cooperation. As outlined by Stano (2008), barriers that exist on an inter-firm level arise from issues surrounding dependency, loss of control over decisions affecting resources, legal barriers, competition, assignment of costs, difference in investment cycles, and insufficient trust and communication. Furthermore, the capital cost of sharing water was a major deterrent for companies (Stano, 2008). Fully integrated IE requires participation from industry, government, community, non government organizations, and third party facilitators to be successful.

Another pitfall in water reuse is the issue of public acceptance. A perceived public health hazard and a "yuk factor" are often associated with the idea of reusing wastewater. There is no set method of swaying public opinion, but education, exposure, and time are often deemed necessary. Public acceptance appears to be highest when the perceived public contact is minimal, protection of public health is clear, protection of the environment is a clear benefit, the costs of treatment technologies and distribution are minimal and perception of wastewater as the source of reclaimed water is minimal (Hartley, 2005). It appears that public acceptance of water reuse is primarily based on perception, which means that public education and implementation strategies are paramount.

With the intent of finding areas conducive to water reuse, the next section summarizes the water use in industrial, commercial, institutional, and municipal sectors of Vancouver and discusses some of the associated economics. Appropriate water users, wastewater sources, geography, and pricing are all considered when finding candidates for water reuse. When all of these factors are taken into consideration, a water reuse scheme that meets requirements that lead to positive public perception and resultant acceptance can be established.

Water Use in Vancouver

One goal of this thesis is to propose a method of reducing water consumption within the City of Vancouver by implementing a water reclamation plan. To do this, temporal and spatial water consumptions patterns and the water distribution infrastructure must be analyzed to identify potential water reuse opportunities. Metro Vancouver has a copious amount of statistics concerning water consumption in the lower mainland and the following section described trends and patterns within the relevant sectors. In particular, the ICI sector will be analyzed as industry is Canada's largest water consumer (Exall, 2004). Additionally, a brief overview of water prices is briefly discussed to give an idea of the past, present and projected water prices.

Vancouver gets its water from Metro Vancouver's Seymour-Capilano water filtration plant, which filters 1.8 billion litres per day, making it the largest plant of its kind in the world. Vancouver's high quality raw water supply currently comes from the Seymour watershed, and originates from a mix of snow melt and rainfall. The treatment plant is also expected to receive water from the Capilano watershed within the next 5 years. Once treated, Vancouver's water supply is regarded as having one of the highest qualities in the world. The water enters the city from North Vancouver at the second narrows crossing and then utilizes 570 feet of available head from the treatment plant to distribute the water through a complex system of pipes, pressure reducing valves, and re-chlorination stations.

As a city, Vancouver's 2007 annual average daily flow and peak daily flow were 331 and 419MLD, respectively. Since 1960 the peak hourly, daily and weekly water consumption has been gradually decreasing while the annual average has seen only a slight increase. During this time the population has steadily increased from approximately 400,000 to 600,000 people and the per capita usage has decreased from 760L/day in 1985 to 520L/day in 2007. The peak hour, day and week have all significantly decreased since the late 1970s (Metro Vancouver, 2007(1)). Estimated residential consumption (metered and unmetered) represents 58% of the region's total consumption. Annual flat rates for multiple family residential connections in Vancouver range from $108.00 - $207.00, depending on whether or not the connection is to a single family residence or a strata duplex. Since 2000, the price of metered water has increased by over 60% from $0.43 to approximately $0.70 per cubic meter in 2010.

As of 2008, the City of Vancouver had a total of 94,029 serviced properties, 13,473 of which were metered (Metro Vancouver, 2008). The City of Vancouver meters dwellings of three units or more, single family dwellings where the property is over a half acre, and all commercial, industrial, institutional, and agricultural connections. Exceptions to this are some city owned and operated facilities such as parks, cemeteries, yards, and public washrooms. In total, about half of the water consumption in Vancouver was metered in 2005. Except for permitted dischargers, customers are billed 85% of the metered water consumption charge for sanitary sewer usage. Exceptions include customers with a majority of water use that does not go to sewer, such as golf courses and breweries, etc.

Of the approximately 94,000 serviced connections in Vancouver, 6,843 were in the ICI sector, with the top three ICI consumers being a brewery, a sugar refining company, and a steam heat distribution utility (Metro Vancouver, 2008). There were 264 industrial connections in 2005, which is a decline from 353 in

1998, but this number has remained relatively constant since 2000. The three ICI sectors with the highest consumption per connection were General Food Products, Dairy and Meat Products, and Forest Products. Metered consumption for all ICI connections in 2005 was 38,956,301 m^3, or 106,730 m^3 per day. In 2005, of the percentage of total water bought from Metro Vancouver, commercial, multiple family, and industrial usage accounts for 21, 22 and 5%, respectively (See Figure 3). The first scenario of the model presented in this thesis takes into account 45% of the ICI sector water usage. Subsequent scenarios take into account commercial and multi-family connections because they account for much larger portions of Vancouver's water use compared to industrial.

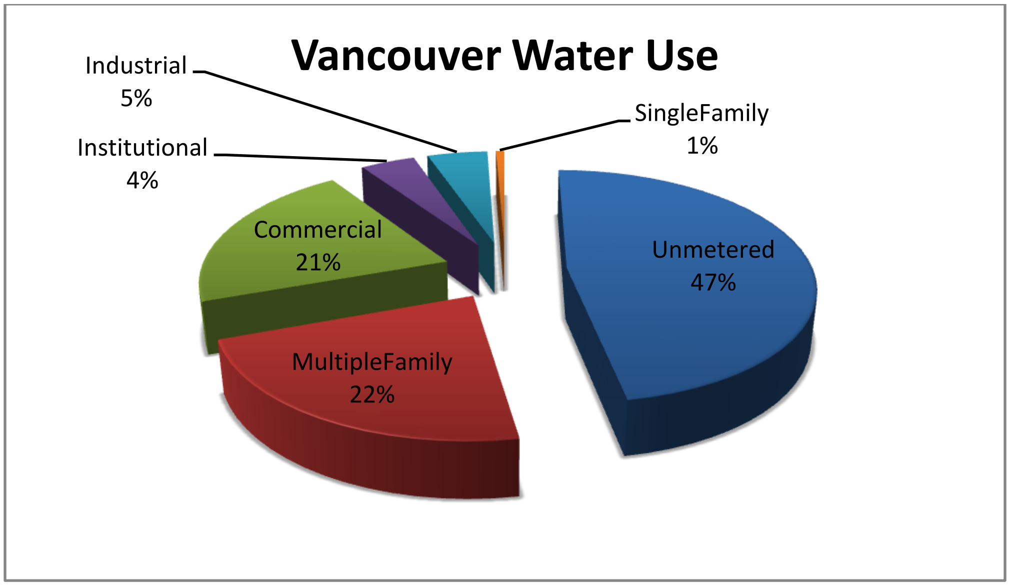

Figure 3 – Vancouver's total water use by sector. Agricultural use is less than 0.1% and not included in this figure. In this pie chart, single family represents mainly residences over a half acre. Unmetered consists of unmetered single family residences, system losses and facilities owned and operated by the city. Adapted from Water – GVWD and Municipal Water Demand by Sector, Policy and Planning Department, 2008.

Once the water is used, 5 pump stations along Burrard Inlet and 2 along the Fraser River near Mitchell Island are used to move the sewage through a system of trunk sewers that eventually make their way to Iona WWTP. A significant amount of electricity is used to pump the sewage generated in the northern half of Vancouver through pump stations along the low lying coastal areas of Strathcona, downtown Vancouver and Point Grey to the Iona WWTP, which is located in the north eastern portion of Richmond. Not having to move this sewage across the entire city would drastically reduce pumping costs and would ease the pressure on the existing sewage conveyance system.

Although the industrial sector only accounts for 5% of the water consumed in Metro Vancouver, industries have the highest usage per connection and represent potential sinks for large volumes of reclaimed water with minimal infrastructure costs. For these reasons, industrial water users represent a starting point for water reuse in highly urbanized areas – so called "low hanging fruit". Combined, commercial and multiple family water usage accounts for over 40% of Vancouver`s total water usage. This is a very significant volume of water, but represents much more dispersed sinks, which require much more infrastructure and planning to implement. The model presented in this thesis will explore the potential for water reuse in all of the aforementioned sectors in an attempt to quantify the volume of potable water that can be supplemented by reclaimed water directly from industries or from a strategically placed satellite water reclamation facility.

Heat Recovery

To further increase the efficiency of resource use, heat energy can be recovered from a wastewater stream before being discharged to a receiving body. Treated effluent represents a very accessible source of energy and addressing heat recovery in conjunction with water recovery makes for a stronger argument when proposing water reclamation projects.

15% of a typical Canadian residential energy bill goes to heating water for use in showers, washing machines, and dish washers. This is the second largest use of energy, behind operating the furnace (Natural Resources Canada, 2006). Estimates by the U.S. Department of Energy (DOE) indicate that the equivalent of 235 billion kWh worth of hot water is discarded annually through household drains, and a large portion of this energy is in fact recoverable. There is potential to recover this energy at a number of points along the sewer line and there is a greater potential to recover the heat on a much larger scale at a WWTP, which sees a significantly larger volume of water. The benefits of heat recovery from wastewater are many and varied. Triple bottom line benefits are often cited where environmental benefits include reduced generation of electricity and natural gas usage, economic benefits include cheaper energy for both the consumer and producer as well as carbon credits. Social benefits include increased partnerships between local governments and businesses, an increased chance for further heat distribution networks, and opportunities for corporations to meet social responsibility objectives.

Energy, usually in the form of natural gas or electricity, is used to heat water. This water is used almost exclusively once before it goes down the drain, through the water collection system to a central water treatment facility where it is treated and discharged to a receiving body where the energy is no longer recoverable. The idea behind heat recovery is that the energy put into the water can be recaptured before it is lost to the environment. This is done by a variety of methods on a number of scales from household heat recovery to centrally located WWTPs. Economies of scale typically support a larger scale heat recovery system, but as energy becomes more expensive and technology becomes cheaper and more effective, smaller scale heat recovery is becoming more and more feasible. The most common application of the recovered energy is heating of water, which acts as a medium of transport for the energy so that a customer some distance away from the energy recovery facility can utilize the energy. This set up is known as a district energy system (DES).

The amount of energy that can be recovered from wastewater and treated effluent depends on the water temperature, flow rate, heat transfer efficiency, and specific heat capacity. The amount of energy extracted can be calculated using the following equation:

$$\Delta Q = m\, c\, \Delta T \qquad \text{(Equation 1)}$$

where

Q = Heat Energy (J)
m = Mass (kg)

c = Specific Heat of Water - 4,187 J/kg/K
T = Temperature (K)

Using this equation it can be found that changing the temperature of a flow of 1MLD by 1°C can yield 4.19×10^9J of energy.

Water has a very good capacity to store large amounts of heat and can be an excellent economic storage medium at a wide range of temperatures. There are, however, economical, logistical and biological constraints by which heat recovery must adhere. Wastewater treatment influent must be above 10°C so as to not disrupt biological wastewater treatment processes, but treated effluent may be treated to as low as 6°C. Low temperature will only be an issue if biological processes are used in wastewater treatment. On the other end, DES water can be heated to upwards of 80°C, but if the temperature is any higher the efficiency of heat transport is compromised and costs tend to increase. DES water temperatures commonly vary from ambient (<25°C) to high temperature (80°C).

There are a number of options for getting the heat from the raw sewage back to the heat end users. The South East False Creek (SEFC) energy recovery facility utilizes a moderate temperature district energy system. The majority of the Olympic Athlete's Village energy comes from the process whereby raw wastewater is screened and sent through a heat pump where, much like a fridge, compressed gas expands in the presence of the screened sewage and extracts the heat from it. The heated gas is then compressed, which heats water that is sent back to the Athlete's Village. The heat pumps allow the re-circulated water to reach temperatures of up to 80°C. Other facilities of this nature also exist in Oslo and Tokyo. Whistler WWTP employs a low temperature system that sends treated effluent, usually 12-20°C, to a heat exchanger that transfers energy to the district energy loop and increases the water temperature from around 4°C to 13-18°C (Johnston, 2009). The district energy water is then sent back to households where individual heat pumps extract the heat. In this situation, less heat is lost during the transport of the water and DES can use cheaper, less insulated pipes to transport the water. However, small heat pumps must be installed in all buildings using the heat.

Generally, a wastewater heat source needs only to provide 60-70% of the peak load condition to meet 95-98% of annual energy requirements in BC (Johnston et al., 2009). During extreme winter temperatures, it is typical for a DES to rely on a back-up natural gas boiler system to meet peak demands. This arrangement has the dual advantage of increasing the potential customer base and making maximum use of the recoverable energy. The Whistler Athlete's Village DES is an example of a low temperature heat recovery system resulting in a 70% reduction in GHG emissions when compared to a business-as-usual approach.

Heat from wastewater may not always be available when required. Peak wastewater temperatures generally coincide with peak wastewater generation, which typically occurs from 7:00am until 9:00am, and from 6:00pm until 8:00pm. Space heating and hot water heating, however, are needed several hours prior to these times; therefore, the DES must be able to store energy. Tanks or in ground sinks such as soil and groundwater can be used for this purpose. Using anticipatory controls to ensure that heat is available when it is demanded could also decrease the amount of heat that needs to be stored.

An ambient temperature DESS may also store energy in the distribution piping for several hours to pre-condition the system before peak heating periods (Johnston et al., 2009).

A study reported the capital cost of 16MLD ambient (20°C), low (35°C) and moderate (80°C) temperature energy systems for the University of Victoria to be 13.1, 12.8 and 12.1 million dollars, respectively and the associated annual O&M costs to be 1.06, 1.04 and 1.01 million dollars, respectively (Stantec, 2010). The differences between the capital and O&M costs are not significant and the payback period for the heat recovery facility would be just under 100 years regardless of the type chosen. Part of the high cost in this situation is due to the 3.2km length of pipe (1.6km each way) required and the need to construct structures to house the heat pumps in the case of the ambient and low temperature options. There are, however, other aspects of the development such as potential for greenhouse gas emission credits and triple bottom line benefits that buffer the less than compelling economic situation.

According to a 2009 report by Metro Vancouver (DiMarco, 2009), building heating accounted for 31% of the lower mainland green house gas (GHG) emissions, cars and trucks accounted for 35%, industrial 20%, other vehicles 10%, and miscellaneous 4% of total GHG emissions. Furthermore, office floor space growth in Metro Vancouver from the years 1990 to 2006 saw the Metro Vancouver commercial core (Downtown and some adjacent areas in Kitsilano) increase 40% to 7.4million square feet. Comparing this to all other Metro Vancouver city cores, which total 2.1 million square feet (an increase of 11%) and to all other areas outside of city cores, which total 9.1million square feet (an increase of 49%), it can be seen that the Metro Core represents a high density of office spaces. These two statistics show that an enormous amount of energy is used for space heating throughout Metro Vancouver and that there is significant potential to exploit wastewater as a source of heat to meet this demand.

When recovering energy from wastewater, a significant flow of easily accessible wastewater must be present in order to make it economical. It is not imperative that the wastewater be treated before energy is removed, but the process is simplified when relatively clean water is used. If water is already being treated to a high level for industrial, commercial and residential reuse, heat recovery is a very economical way to further utilize wastewater. The model presented in this thesis combines the idea of water recovery with heat recovery by optimally placing a satellite WRF to maximize the volume of water reused and, in turn, maximizing the amount of heat being recovered from a resource that is currently being wasted.

Geographic Information Systems

One of the ways to strategically place a satellite water reclamation facility is to utilize a spatial referencing program to optimize a number of variables that are otherwise difficult to integrate. A geographic information system (GIS) integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information (ESRI, 2010). GIS uses computers and software to explore the fundamental principal of geography. It is used to inventory, analyze, and manage aspects of the world and since the 1960s has been used to aid in the analysis of water systems (Males, 1990). A GIS takes the numbers and words from databases and puts them on a map, which can then show patterns in the data that may otherwise be missed.

In a paper by Leitão, et al. (2005), the authors were faced with the problem of providing wastewater systems to small, dispersed communities in rural Portugal. Two algorithms, known as add and drop, were used to find the optimal number of WWTP such that the initial cost and the cost of the associated infrastructure was minimized. The add algorithm starts with a single wastewater treatment facility and proceeds to sequentially add facilities until the cost starts to increase. The drop algorithm works in the opposite way in that it starts with a facility at every potential site and removes facilities until the solution cost increases. In this model, the algorithms were implemented directly into ArcGIS, which provided the spatial information of an area with a varying number of wastewater treatment facilities.

Utilizing GIS for a different application, a Sri Lankan river catchment has been significantly deteriorated by a number of point and non point pollution sources. Wastewater treatment was needed to prevent further ecological deterioration and Ratnapriya and De Silva (2009) faced technical, environmental, economical, and topographical constraints when trying to find a suitable location. Using a digital terrain model (DTM) of a subcatchment, areas with a slope greater than 15%, forested areas, inhabited areas, and areas of potential flooding were appropriately buffered using the buffer tool in ArcGIS. This left 23% of the subcatchment to be deemed suitable for WWTP construction. Additionally, a walkthrough of the subcatchment was done to identify point and non point sources of pollution. Combining the walkthrough data with GIS analysis, the authors were able to locate and propose necessary types of wastewater treatment. An economic analysis was not mentioned in this paper.

Another application of GIS in locating wastewater treatment plants was seen in a paper by Zhao et al. (2009). A proposed method of locating a treatment plant utilized the eco-suitability evaluation method, which integrated social, economic, and ecological factors by using fifteen 'ecological indices' which rate how sensitive water bodies, riparian zones and land areas would be to the development of a WWTP. With the use of GIS and an analytical hierarchy process the authors were able to amalgamate data from a large number of sources and subdivide the results into three categories of suitability for potential WWTP location.

Virtually all of the data collected in this thesis is input into the GIS program ArcMap. Because of the popularity of GIS, data specific to Vancouver or any major city, for that matter, is fairly easy to access. (However, getting it for free is different challenge). The data is entered in a number of different layers all displayed on a single map. Data can be entered as a point (each individual water user), a line (road ways and sewer lines), or a polygon (zoning districts). Each feature has an associated "attribute table", which is used to link data to each point, line or polygon. For example, an attribute table for a company would have the company name, location coordinates, address, influent and effluent volumes, influent and effluent qualities, and elevation. Once in ArcMap, the data is then analyzed to elucidate relationships among the water users.

The monetary investment required to make water reuse a reality is daunting and a number of measures must be taken in order to mitigate costs. GIS is an effective tool for facilitating industrial ecology by visualizing and understanding spatial relationships between companies and quantifying transport requirements (Stano, 2008). The program is often integrated as one part of a larger model, as in some of the aforementioned cases and in the model presented in this thesis. The subsequent three sections of this model explain linear optimization and how it is combined with GIS to make a functioning model that attempts to quantify the reuse potential in Vancouver.

Python Programming Language

Linear optimization can be performed using large amounts of data with the use of modern mathematical solvers such as MATLAB. However, manually inputting the data into these programs can often be very tedious and time consuming. Python programming language is a open source, object oriented programming language that was developed in the late 1980s with an emphasis on readability. Using python scripts, a user can directly access data in ArcGIS, extract and format it in such a way that it is easily transferable to MATLAB. This allows for large amounts of information to be automatically generated and formatted with relative ease. With upwards of 400 lines of code in the model, the python coding presents a steep learning curve for individuals without prior programming experience. However, python was designed to be more user friendly than other popular programming languages such as java, Perl or C.

MATLAB

MATLAB, short for matrix laboratory, is a numerical computing environment that allows for matrix manipulations, plotting of functions and data, implementation of algorithms, and creation of user interfaces. Used for its numerical manipulation abilities and Simulink's modeling and simulating abilities, MATLAB is utilized across a number of fields including engineering, science, and economics. This thesis utilizes only one of the many built-in functions called 'linprog', which is a linear programming function. The linear program function requires that data from GIS (the linear objective function, the constraints, and the upper and lower bounds) to be input as either vectors or matrices. The following section briefly outlines the concepts behind optimization and linear programming.

The previous three sections introduced the three computer programs that make up the skeleton of the model presented in this thesis. How they are combined and utilized is summarized in Figure 4.

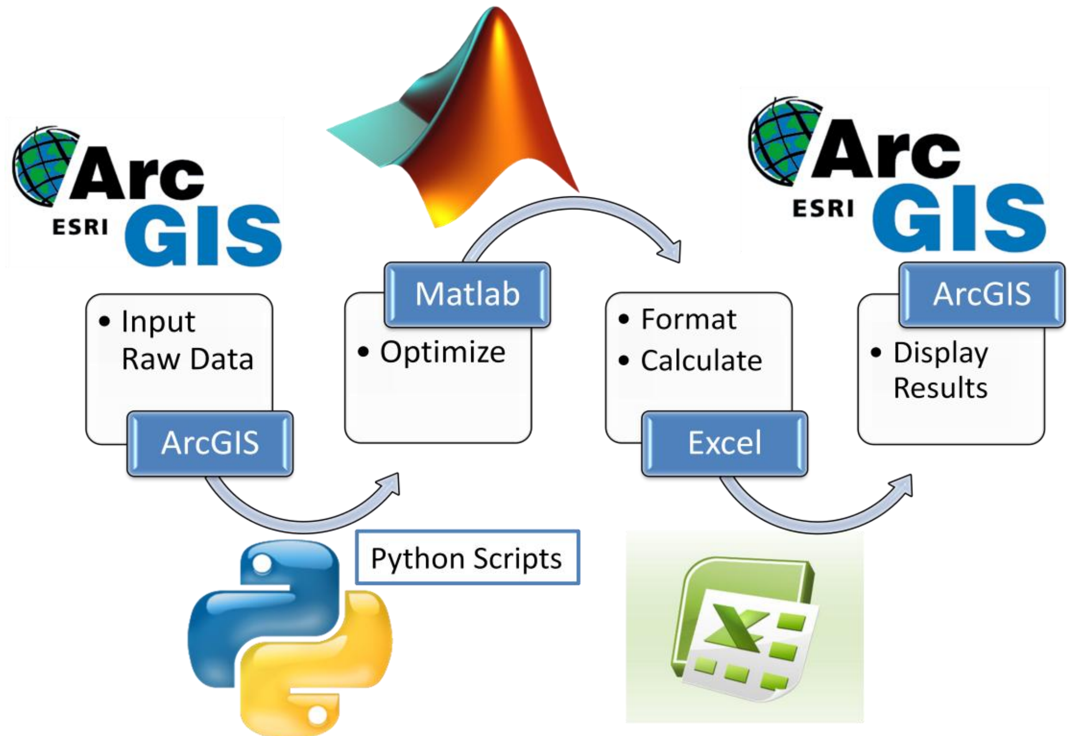

Figure 4: The model represented in a flow chart

Optimization and Linear Programming

Optimization is a mathematical technique for finding a maximum or minimum value of a function of more than one variable subject to a set of constraints. Linear programming is a technique for the optimization of a linear objective function, given a list of requirements that are represented as linear equations. The general idea behind this is to find the *best* answer to a question or problem given that your variables are only able to exist within a certain range of values.

Linear programming has three main components (Steinburg, 1974)

1) A linear objective function – the quantity to be optimized

$$z = \sum_{j=1}^{p} (c_j x_j) \qquad \text{(Equation 2)}$$

2) A linear constraint set
3) Non-negative restrictions on the variables

where the volume of water recycled is maximized given constraints on water quality, water volume and electricity.

A linear programming model statement has a widely applicable and universally appealing structure in that it places an objective or goal alongside constraints. The objective, the volume of water to be recycled, is the element to be optimized. Other objectives can include minimization of cost or maximization of profit. Constraints are conditions that any and every solution must satisfy. Refer to section 4 for an in depth description of the constraints as well as general model development.

Two types of linear programming are considered in this thesis, where multiple objective functions are brought into a single objective function and then solved. The weighting method brings all objectives into one objective function and relative weights are assigned to each objective. The constraint method solves the single resultant objective function while converting the other objective functions into constraints. Linear programming methods take the general form of

$$\text{Maximize } z = C\mathbf{x} \qquad \text{(Equation 3)}$$

$$\text{subject to: } \mathbf{Ax} \leq \mathbf{b} \qquad \text{(Equation 4)}$$

Where

A = Constraint coefficient
b = Constraint
x = Decision variable
C = Cost Coefficient

This can be generalized by (Steinburg, 1974):

$$\begin{array}{c} a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n \geq b_1 \\ \vdots \qquad\qquad\qquad \vdots \\ a_{p1}x_1 + a_{p2}x_2 + \ldots + a_{pn}x_n \geq b_p \end{array} \qquad \text{(Equation 5)}$$

$$x_j \geq 0, \qquad \text{(Equation 6)}$$

Given the p*n coefficients of a_{ij} and the p by 1 constraint vector

$$b = \begin{pmatrix} b_1 \\ \vdots \\ b_p \end{pmatrix} \qquad \text{(Equation 7)}$$

The optimization comes about by finding an n by 1 vector **X** satisfying Equation 5 and such that

$$z = c_1x_1 + c_2x_2 + \ldots + c_nx_n, \qquad \text{(Equation 8)}$$

is a maximum and the c_j is given. A vector X which satisfies (Equation 4) is called feasible and if it also satisfies equation (Equation 8) it is called optimal feasible. The conditions or constraints (Equation 5) are called feasibility conditions (Steinburg, 1974). During computation of the optimal solution, the decision variable is changed until an optimal solution is reached. MATLAB performs this laborious operation in a matter of seconds.

In a paper by Chu et al., 2004, linear programming was used to estimate water reuse potential on a national scale in China. The model consisted of ten physical constraints and five economic constraints, and included 342 small and large cities in 31 provinces. The authors of this paper were able to take into account differences in water prices by region and by industry into their model, which allowed them to cover a very large region. The data collection in this paper was extensive, but there were still many regions with a large area where the economic and/or water data was not available. Having economic constraints in this model was vital as industrial and agricultural water is significantly cheaper than commercial or municipal water. This resulted in much lower reuse rates for the municipal and commercial sectors. In this analysis, it was the areas with high population density, water scarcity, and high water prices that had the largest potential for water reuse. A prime example of this scenario was found in Beijing.

In the present thesis, linear programming is utilized to find the optimal solution to “what is the most water that I can recycle within a particular set of water users”, when the statement is expressed as a linear objective function. Section 4 will go into detail about the development of the linear objective function and the constraints that make up the optimization section of the model, which take place in MATLAB.

Section 4 - Model Development

The model used in this thesis is based on the model developed by Stano, 2008. It was initially developed to assess the potential for industrial water sharing to aid in the development of water exchange networks. The model looked at the effluent qualities and required influent qualities of all water users in a theoretical industrial park and found potential opportunities where one company's effluent could be used to supplement the potable water use of another company. The basic skeleton of the Stano (2008) thesis will be used for the same purpose in this thesis, with minor modification to simulate a variety of scenarios. Mathematical optimization of objectives based on water usage and electricity is then performed, given constraints on the water quality, water volume, and electricity. GIS is also utilized to incorporate the geographical location such that installation requirements can be calculated and optimal sharing potential can be analyzed. At the time of development, the required data was not available and the model was populated with fictitious data to demonstrate its potential.

Data specific to Vancouver was gathered and the model was run to find potential reuse between discharge permit holders within the VSA. Due to the limitations imposed by the water quality constraints, the cascading potential is limited because permitted dischargers typically discharge low quality wastewater. To get around this barrier, modifications to the existing model were used in order to explore options to recycle more than wastewater from permitted dischargers. Firstly, a theoretical satellite water reclamation facility was included to assess the potential for reuse within industry with a constant supply of treated wastewater. Secondly, water meter data was used to add industrial, commercial, institutional, and multifamily residential users into the model and to find the reuse potential using treated wastewater among all metered water users in the targeted areas of Vancouver.

The model consists of three separate computer programs: ArcGIS, Python programming language, and MATLAB. A general description of each program can be found in section 3. An overview of how the model works is as follows: Raw data is input into ArcGIS as data points with attribute tables, see Table 3. Through built-in functions in ArcGIS, a matrix of distances between all data points is generated. Python programming language is then used to communicate directly with ArcGIS via two separate scripts. (For a print up of all scripting code used, see Appendices A and B). The first script uses the data generated by ArcGIS to make a number of lists that are used to calculate pumping requirements from a water reservoir to each company, from each company to a WWTP, and between companies. The script also finds potential sources and sinks for the cascaded water and how much each company can share and prints these lists for the next python code. The second python script is then used to format all of the lists for input into MATLAB. Once all of the information is manually transferred from Python to MATLAB, MATLAB's linear programming function, 'linprog', is used to maximize the linear objective function. Matlab automatically generates an excel spreadsheet with the results, which are then tabulated and analyzed in excel. From there, the information can be displayed using ArcGIS.

The first thing that needs to be done in any GIS based model is to develop a base map of the area of interest. In this case, the area of interest is the VSA. Due to the complex, atypical shape of the VSA, a file outlining the VSA had to be obtained from Metro Vancouver. Additionally, a map of the VSA elevation and a map of the area's roads were obtained from the UBC geography department. The road map was compared to the City of Vancouver's water and sanitary sewer maps and it was found that for this model's purposes, the road map could be used in place of the sanitary main map because of the sewer map's numerous discontinuities, which make it difficult to create networks in ArcGIS. With a road map, an elevation map and a specified geographical area of interest, data points can readily be added and analyzed using a reasonably accurate topographic representation of the VSA within the GIS program.

In the first scenario, the data points used in the model are the 102 permitted dischargers in the Vancouver sewerage area. Once entered onto the base map, a GIS function called 'OD (origin-destination) cost matrix' generates an array of distances between each of the companies. Because there were 102 companies, the OD cost matrix was 102x102, or 10,404 entries. These distances were then combined with elevation data to calculate pumping requirements between each company. Once the data is generated within ArcGIS, the data must then be transferred to MATLAB for optimization using Python scripts, which can be found in Appendices A and B.

It should be noted that due to the increased number of water users, changes had to be made to the original python and MATLEB scripts in order to cut down on the required computing. In its original form, an average PC with 3GB of memory froze when the number of companies in the model exceeded approximately 50. The majority of the modifications involved creating sparse matrices in MATLAB instead of in Python and having to manually transfer them to MATLAB. MATLAB, which was designed largely for the creation and manipulation of matrices, is capable of creating very large sparse matrices with minimal memory requirements. The MATBLAB scripts can be found in Appendix C.

Once properly transferred to MATLAB, the mathematical optimization can occur. In MATLAB the most important aspect of the model is the linear objective function (LOF) which determines what is being optimized. In the case of this model, the LOF was formulated such that the volume of water being reused is being maximized. The following is a brief explanation of how the optimization model was formulated. A more in depth explanation of the mathematical development can be found in Stano, 2008.

Objective Function

Company a requires I_a m^3/year of water of quality IQ_a and discharges O_a m3/year of quality OQ_a. An exchange fraction, $Y_{a,b}$, is introduced to represent the fraction of industry *a*`s water that can be provided by industry *b*`s discharge.

The LOF takes the form of

$$\text{Maximize} \quad \sum_{a=1}^{n}\sum_{b=1}^{n}(Y_{a,b} * I_a) \qquad \text{(Equation 9)}$$

The exchange fraction, $Y_{a,b}$, is known as the decision variable. This is the variable that the computer optimization algorithm changes until an optimal solution is reached. Note that in the first scenario there are 10,404 decision variables. The values that $Y_{a,b}$ can take are directly constrained (hence, *constrained* linear optimization) by mass balance, water quality, and indirectly constrained by the electrical consumption associated with pumping the water as well as the cost associated with the infrastructure needed to move the water. These constraints need to be expressed mathematically to be incorporated into the MATLAB algorithm.

Mass Balance Constraints

The first constraint on the decision variable is a mass balance constraint that states that company *a* cannot accept more water than it currently uses. Mathematically,

$$Ya,b \leq 1 \qquad \text{(Equation 10)}$$

$$\sum_{a=1}^{n} Ya,b \leq 1 \qquad \text{(Equation 11)}$$

Furthermore, the volume of effluent that company 'b' gives to company 'a', $x_{a,b}$, cannot be more than company *b* has to give. The constraints on $x_{a,b}$ are as follow:

$$x_{a,b} = \frac{Y_{a,b} \times I_a}{O_b} \leq 1 \qquad \text{(Equation 12)}$$

$$\sum_{b=1}^{n} x_{a,b} \leq 1 \qquad \text{(Equation 13)}$$

where

O_k = Annual volume of water effluent from Industry k.

Water Quality Constraint

Another important part of identifying potential sites for water exchange is identifying water of appropriate quality. As the algorithm searches for potential matches, it checks to see it the effluent quality of company 'b' is equal or less than the influent quality required by company 'a', then $Ymax_{a,b}$ is set equal to O_b / I_a (note that if O_b / I_a is greater than one, then Ymax is set equal to one). If the company 'b''s effluent does not meet the requirements of company 'a', then Ymax is set equal to zero.

Non Negativity Constraint

The final direct constraint on the exchange fraction says that a company cannot give or receive a negative volume of water.

$$Y_{j,k} \geq 0 \qquad \text{(Equation 14)}$$

Electrical Constraint

Electricity is required to pump potable water from a treatment facility to users and then to pump wastewater from each generation point to the WWTP. Because of its topographic layout, Vancouver uses the vast majority of its electricity to move its wastewater and requires very little to distribute its potable water supply. This is because Vancouver, unlike the majority of cities, has its water source located about 500 feet above most water users and the existing elevation head can be utilized for distribution. In fact, most parts of Vancouver require pressure reducing valves. An electrical constraint is formulated such that the scenario the model simulates (direct cascading among industries, direct cascading with a treatment plant, sharing between all metered water users), uses equal or less than the amount of electricity used in the current set up in Vancouver. The energy consumed by pumping water is a function of the distance the water travels through a pipe and the change in elevation. As adapted from Stano (2008), the energy is calculated as follows:

$$E\left(\frac{kW\hbar}{m^3}\right) = \left(\frac{g\left(\frac{m}{s^2}\right) \times \Delta Z(m)}{\eta} + \frac{4 \times f \times L(m) \times v^2\left(\frac{m^2}{s^2}\right)}{\eta \times D(m) \times 2}\right) \times \rho\left(\frac{kg}{m^3}\right) \times \left(\frac{1kW\hbar}{3{,}600{,}000J}\right), \quad \text{(Equation 15)}$$

where

E = energy per volume of water (kWh/m^3);
g = gravitational constant (9.81 m/s^2);
Δz = change in elevation (m);
η = pump efficiency (0.65);
f = friction factor (0.004);
L = Length of pipe that water flows through (m);
v = velocity of water (m/s);
D = diameter of pipe (m) and
ρ = density of water (1,000 kg/m^3).

In this model, electrical use is constrained such that the modeled scenario (the scenario in which water reuse is occurring) must use less than or equal to the existing electrical consumption in Vancouver. Mathematically, this is expressed as a function of;

- the energy required to get potable water to the companies, $E_{a,w}$;
- the energy required to transfer water between users or between users and the WRF, $E_{a,b}$ and;
- the energy required to pump the water from the users to Iona WWTP, $E_{ww,a}$;

$$\sum_{a=1}^{n}\sum_{b=1}^{n}(Ya{,}b)\sum_{a=1}^{n}\sum_{b=1}^{n}(E_{a,b}{*}Ia - E_{a,w}{*}Ia - E_{ww,a}{*}Ib) \leq EEC \quad \text{(Equation 16)}$$

Where:

EEC = existing electrical consumption =

$$\sum_{a=1}^{n}(E_{a,b} * Ij + E_{ww,a} * O_a). \quad \text{(Equation 17)}$$

Effectively, this constraint forces the program to find the maximum amount of sharing using a finite amount of electricity. This means that, given the appropriate water quality, the companies that require the least pumping are chosen as sinks. This does not, however, minimize the amount of pipe required because although it may require more pumping, the cost of installing pipe to a company that is 500 meters away is very low if you have already laid 450 meters of pipe to the company next to it. Furthermore, it may require less electricity to pump to a sink significantly downhill compared to a closer, uphill sink.

All of the above constraints are applied exactly how they are presented in this paper in both scenario 1 and 2. Scenario 3, however, is slightly different in that it only considers the sharing potential between the satellite WRF and the water users. The linear object function for the third scenario is as follows:

$$\text{Maximize} \sum_{a=1}^{n} (Y_{a,s} * I_a), \qquad \text{(Equation 18)}$$

where:
$Y_{a,s}$ = exchange fraction between company a and satellite water treatment plant.

This algorithm does not look at the potential cascading between metered water users because the vast majority of these users are commercial and multi-family and produce wastewater of an unsuitable quality. Furthermore, the computational requirement to consider that many water users is extremely large. Because the satellite WRF treats water to a constant quality, the water quality constraints to not have to be taken into account, further reducing the computational requirements. All other data and constraints remain unchanged from the first two scenarios.

Data Gathering

The majority of mathematically based model development, what can be referred to as the skeleton of the model, was performed by Stano (2008). All of the above constraints and functions are performed on the data when it is input into the model. The constraints and linear objective functions remain constant regardless of the city or area analyzed. The vast majority of the time requirements to operate the model arise from gathering data specific to the area of analysis. The data will vary depending on the situation and end goals, but will typically require GIS data, water user influent and effluent quality and quantity requirements, geographic location, and elevation. The following section outlines the processes used to obtain the data and summarizes the results.

To start the model, a map of the VSA has to be constructed from a number of data sources. The final GIS map contained elevation, roads, the VSA boundary, water bodies, pump station location and associated electrical usage/volume pumped, park location, zoning districts, water meter information, aerial photographs (orthophotos), and permit information (location, discharge volume, BOD and TSS concentrations of discharge).

Raw Data for All Companies	Source
Company Name	Permit Data[1]
Influent Volume	Water Meter Stats[2], Literature
Effluent Volume	80% Assumption[3]
Required Influent BOD	Literature, Personal Communication
Required Influent TSS	Literature, Personal Communication
Effluent BOD Concentration	Permit Data[1]
Effluent TSS Concentration	Permit Data[1]
Greater Vancouver Elevation	UBC Geog Department.

Table 3 - Table of raw data input into GIS and the corresponding source of information. [1] Metro Vancouver. [2]City of Vancouver [3]Assumption used in Stano, 2008.

Geographic Location, Influent and Effluent Volumes

Each point on the GIS map represents a potential source or sink has to be populated with data from a number of differences sources as outlined in Table 3. To generate enough data points to make the model representative of the actual reuse potential of an area of Vancouver, a variety of data from more than a hundred water users had to be incorporated. Data relating to geographic location and water usage is not difficult to obtain; municipal listings will often contain company addresses and municipalities will often meter the majority of its largest water consumers. Effluent volumes can be estimated with reasonable accuracy by assuming 80% of industrial influent is discharges as effluent (Stano, 2008).

Effluent Water Quality

When searching for potential water cascading opportunities between industries, influent and effluent concentrations must be combined with the water end use and influent concentration requirements. Influent water quality requirements and water end uses are much more difficult to obtain, often because this information is considered to be proprietary. The most straightforward way of obtaining effluent constituent data would be to take effluent samples of individual dischargers. However, sampling each individual industry's effluent characteristics would result in a very large number of samples, a process which is both time and cost prohibitive. Conveniently, many of the largest water users in this model's area of interest are permitted dischargers and their effluent quality is known because they are required to monitor their effluent as stipulated in the permit requirements. High rise buildings are considered later in this thesis because they make up a number of large water users. Their effluent, however, is assumed to be comparable to domestic wastewater and is not considered for direct reuse.

Literature values exist for a number of different types of industrial effluent. However, depending on local regulations, effluent pre-treatment may be required before it is discharged into the sewer system. For this reason, literature values were deemed to be unrepresentative of actual Vancouver industrial effluent and the data from permitted dischargers' effluent data alone was used to generate the database for effluent characteristics. See Table 4 for a list of average BOD and TSS concentrations in Vancouver permit holders' effluent. When more than one company's data was available for a specific type of industry, the effluent values were averaged. Some BOD data is not available because the BOD concentration in industry's effluent does not warrant a permit and subsequent monitoring. For the purposes of the model, the unavailable BOD concentrations were assumed to be 10mg/L.

Industry	BOD (mg/L)	TSS (mg/L)
Bakery	1224.2	458.2
Beverage (Brewery)	1924.0	386.9
Beverage (Juice)	445.0	61.8
Chemical / Petroleum	12.3	12.4
Commercial Film Processing	n/a[1]	4.3

Industry	BOD (mg/L)	TSS (mg/L)
Commercial Laundry	63.1	37.0
Concrete Manufacturer	n/a[1]	74.0
Construction Site	n/a[1]	50.1
Dairy Processing	1227.7	440.2
Food Packaging	166.6	86.32
Garment Manufacturing	240.5	46.4
Gas Station	n/a[1]	9.5
Laboratory	n/a[1]	38.2
Meat Rendering	1562.2	201.8
Metal Finishing	n/a[1]	90.0
Misc Food Production	601.0	178.2
Poultry Processing	713.5	407.4
Rail/Bus/Airplane Repair	n/a[1]	17.3
Restaurant	772.0	275.7
Seafood Processing	454.1	224.5
Sugar Refinery	1046.0	194.4
Waste Disposal/remediation	650.8	78.0

Table 4 – Averaged industrial effluent BOD and TSS concentration s. Specific company names were left out for privacy reasons. [1]Concentrations were assumed to be 10mg/L when input into the model.

Required Influent Water Quality

In order to generate required influent concentration data, a number of literature sources were consulted. Fortunately, there are many uses for reclaimed water that are common among industries. Cooling, boiler feed water, equipment washing and toilet flushing are common examples. The USEPA regulations state a maximum of 30 mg/L for BOD and TSS and the MSR regulations state a maximum of 45mg/L BOD and TSS for all restricted industrial uses. However, most literature surrounding industrial reuse states that suspended solid concentration should be much below 45mg/L if it is going to be used for purposes such as industrial cooling water, equipment washing, and boiler water makeup (Roeleveld & Maaskant, 1999, Asano et al., 2007, Selby & Helm, 1996). In other words, although 30-45mg/L is the regulated limit, much lower concentration are required for practical purposes. As outlined in section 3, there are also a number of other constituents that can be problematic for industrial processes. For these reasons, unrestricted reclaimed water was not considered for the majority of industrial uses. Table 5 outlines the requirements for some common industrial processes.

	COD	BOD	Dissolved Solids	Suspended Solids
Boiler Feedwater[1]	5	n/a	600	7.5
Cooling water[1]	75	n/a	1000	5000
Chemical[1]	n/a	n/a	1000	5
Petroleum and Coal Products[1]	1000[2]	n/a	1000	10
Primary Metal[1]	n/a	n/a	1500	3000
Food Canning[1]	n/a	n/a	550	12

	COD	BOD	Dissolved Solids	Suspended Solids
Equipment Washing[2]	n/a	45	n/a	45
Toilet Flushing[3]	n/a	10	n/a	10

Table 5 - A collection of industrial water quality requirements [1]- Asano et al., [2] Nobel 1998 and [3] BC MSR

Water End Use – Reuse Potential

Once knowledge of required water quality is amassed, water end uses become the next data to be gathered. The uses for water that can be supplemented with reclaimed water are of particular concern to this thesis. Unfortunately, like effluent constituent data, water end use data is often considered proprietary data. Some information sources, however, do exist (Division of Pollution Prevention and Environmental Assistance, 2009, Shultz, 1999, Gelman et al., 1989). However, some of the information may be bias because many of the industries have already implemented water reducing measures and are consuming less water in some of their processes. Therefore, information from these sources likely represents a low estimate of Vancouver industries' reclaimed water reuse potential.

Industrial water requirements are many and varied, and recycled water cannot be substituted for potable water in all cases. Certain activities such as food processing and direct potable uses are specifically prohibited by virtually all western water reuse policies for public health and liability reasons. In the modeled scenario where industries are only allowed to directly cascade between themselves without treatment, the 102 permitted industries were taken into account as potential sinks and sources of water. Due to the policies imposed by the municipal sewage regulation and the liability associated with microbial contamination as a result of using recycled water in food processing plants, food processing industries were not included as potential sinks of recycled water and their water inputs were set to zero.

The gathered data was not always in a form directly usable by the program. In the first modeled scenario, the volume of water a company was able to accept was not 100% of a company's documented yearly water use. Rather, the volume of water an industry was able to obtain from another industry was limited by the individual company's end use for the water. That is, if a company is only able to supplement 50% of its current water use with reclaimed water, then the exchange fraction (the cumulative volume a company can accept from other companies expressed as a fraction of the company's total water use) is set to 0.5,

$$\sum_{a=1}^{n} Ya,b \leq 0.5 \qquad (19)$$

Although water use is very industry specific, assumptions of comparable water uses across similar industries such as seafood processing plants and metal plating facilities can be made. Industry water end uses were taken from a combination of interviews and literature. Averages were taken if more than one source of data was available for a particular industry's water use. Furthermore, the data obtained from conversation with one industry representative was used for all industries classified under the same industry type (ie. seafood processing, metal finishing). This assumption was made because there are often cultural, economic, climatic, technological, and regulatory factors that influence companies in one country or region's water use for similar processes (Asano et al., 2007). A dairy processing plant in

Australia, for example, may be in a highly regulated, environmentally sensitive region experiencing a drought and therefore have economic and regulatory incentives to cut down on water use and to produce a cleaner effluent, which is obtainable because of readily available water treatment technology (DAFF, 2007). A similar plant in India, on the other hand, may face very different restrictions on water use. Refer to Table 6 for a breakdown of reclaimed water use potential among ICI and high-rise water users.

	Industry	%	Main Use
Industrial			
	Brewery	66	Equipment Cleaning
	Refinery	70	Cooling and Boiler Water
	Poultry Processing	30	Equipment Cleaning
	Sugar Refinery	30	Equipment Cleaning and cooling
	Laundries	5	Toilet Flushing
	Dairy Processing	30	Equipment Cleaning
	Meat Processing	30	Equipment Cleaning
	Construction	80	Equipment Cleaning, dust suppression,
	Metal Finishing	90	Rinsing, cooling, solution
	Waste Disposal/remediation	75	Cleaning
	Commercial Film Processing	20	Toilet Flushing
Commercial			
	Rail/Bus repair and service	60	Equipment/Vehicle Washing
	Laboratory	30	Toilet Flushing, equipment washing
	Hotel	55	Toilet Flushing, heating, cooling, landscape
	Restaurant	30	Toilet Flushing, cooling
	Gas Station (Carwash)	50	Equipment/Vehicle Washing, toilet
	Office Building	60	Toilet Flushing, cooling, landscape
	Parking Lot	90	Washing, toilet flushing
	Produce	5	Toilet Flushing
Institutional			
	School	75	Toilet Flushing, landscape, cooling
	Hospitals	45	Toilet Flushing, heating, cooling
Residential			
	High-rise Apartment	30	Toilet Flushing, cooling, landscape

Table 6 – A summary of the percentage of total water consumption that can be supplemented with reclaimed water and the main uses for the reclaimed water.

The following example may help clarify the idea of an exchange fraction. A food processing plant uses a total of 10,000m^3/year of potable water but only 3,000m^3 of that water can be supplemented by recycled water for, say, cooling, and the rest of the water is used as process water and comes into direct contact with the final food product. The exchange fraction for that particular industry is therefore set to 0.3, which represents 3,000m^3/year.

As previously mentioned, parks were included in the third scenario as potential reclaimed water users for the drier summer months. When calculating irrigation requirements for parks, an irrigation and drainage specialist from UBC was consulted regarding the volume of water thought to be acceptable for proper irrigation (Chieng, 2009). Taking into account climate and generalized local geology, an estimate of 400-600mm/year on average was suggested as appropriate for Vancouver green space. Therefore an average of 500mm/year*area was used in calculating water demand for park irrigation. Furthermore, the approximate surface area of the parks was estimated using the distance tool in ArcGIS combined with the Google Maps satellite view to identify all green space in the area of interest. The volume calculated using this method was a yearly total and would be used almost exclusively during the dry summer months. This value is highly dependent on climate and will vary largely outside of Vancouver.

Electricity

To develop the electrical requirements as outlined in section 4, the electricity required to pump water from the Seymour-Capilano Filtration Plant to the water users, between cascading industries and from individual water users to Iona WWTP must be calculated. This can be estimated using equation 15 or information can be taken directly from the municipality. The city of Vancouver supplied electrical consumption information for both Columbia and Harbour pump stations (this information can be made available upon request), which allowed for a more accurate quantification of the amount of electricity used to pump wastewater to Iona WWTP. Theoretical pumping, as in the case of water cascading between industries, required the use of equations 16 - 18.

Siting a Potential Wastewater Reclamation Facility

The second and third scenarios consider a theoretical water reclamation facility to supply water users with reclaimed water. Finding the best location for this facility is subject to a multitude of geographically sensitive economic, environmental and social factors. This problem becomes the next topic to be addressed in this thesis.

There exists a number of spatial location models that utilize algorithms to solve a particular question, whether it is maximizing the number of people being served or minimizing the cost of a facility. The models generally find answers to questions like how many facilities to locate, where they should be located, and what their capacity should be (Leitão, et al., 2005). In determining the optimal number of treatment plants and/or their locations, the treatment cost and transportation costs must be balanced. In the case of siting a satellite water treatment plant within a fully developed area of Vancouver, a number of confounding social, environmental, and economic factors make for a level of complexity that would significantly reduce the effectiveness of most algorithms. The following section outlines the considerations taken into account when siting the potential WRF in the VSA.

Considerations in Siting

The siting of Iona wastewater treatment plant allows for the advantage of being away from urbanized areas and being close to a receiving body of water that, with the help of an outfall pipe, has very good effluent dilution capabilities. It is a large plant that benefits from economies of scale and it utilizes relatively uncomplicated processes, which make it easier to find knowledgeable personnel and potentially cheaper to operate. However, because of Iona's relative remoteness the infrastructure and pumping required to transport treated water is quite significant. Furthermore, it is not currently capable of meeting some of the more stringent reuse standards consistently. Upgrade to a minimum of secondary treatment and potentially filtration would be required to consistently meet these standards.

When planning to integrate a satellite treatment facility into an existing collection system, a plethora of factors must be considered. First and foremost, and partially what this thesis deals with, is the identification of local near-term and future reclaimed water needs. This task alone can be quite difficult and requires a significant amount of data to be reasonably accurate. Factors to be considered are the types of industry and commerce in the area of study, the type of reuse applications at each, amount of water required, diurnal, seasonal or yearly variations in water demand, water quality requirements, potential geographic location of satellite plants, and the distribution area's general topography. One of the most difficult parts of planning is trying to predict how the aforementioned list will change in 1,5,10 and 25 years (Asano et al., 2007). Other considerations include integration with existing facilities, potential growth of the area, public perception, legal aspects and institutional issues, economic considerations, environmental considerations, and governing regulations (Asano et al., 2007).

Once most of the aforementioned logistics have been taken care of, there are still a number of factors that need to be taken into account during and after the construction of a centrally located and likely controversial facility. Issues not limited to soil, geology and land use, hydrology and water quality, archaeology and heritage, noise, vibration and lighting, dust and air emissions, health and safety, odour and use of public lands need to be considered. Due to the controversial nature and the stigmas surrounding a water reclamation facility, public input would be necessary to gauge public support, address issues, spread information, and aid in decision making. Additionally, the facility would have to be constructed far enough away from residential, commercial, and institutional areas to avoid public outcry. Hence, when narrowing down potential locations for the WRF, the buffer tool in ArcGIS was utilized to construct a 200m buffer zone around all residential, commercial, institutional, and specially zoned areas in Vancouver. Effectively, the only areas remaining are industrially zoned areas with at least 200m between them and the nearest commercial, residential, institutional, or special zoned land. See Figure 5.

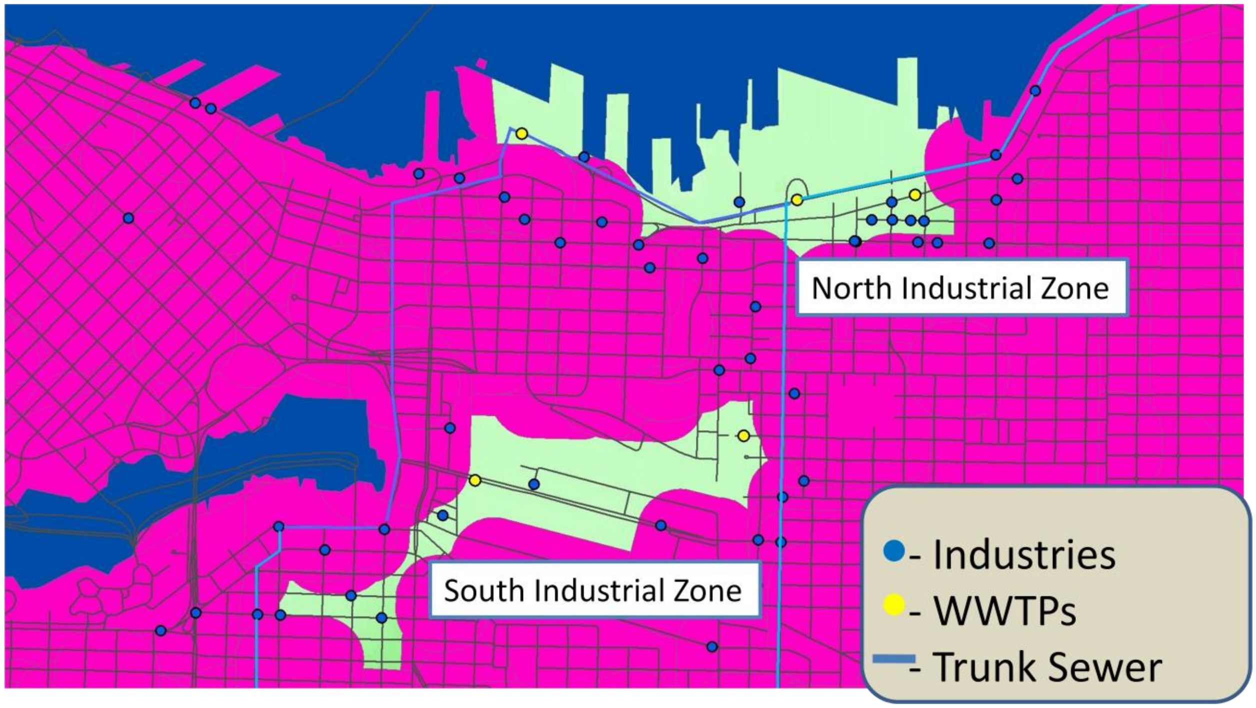

Figure 5 – Downtown and Strathcona areas suitable for a satellite WRF and their consequent locations. The pink areas represent area within the 200m buffer zone.

Referring to Figure 5, the pink area denotes the land inside of the buffer zone and the light green denotes land outside of the buffer zone. From Figure 5 we can see that there are two main strips of land that fit the 200m buffer criteria, the north and south industrial zones. The southern zone is located along the central segment of Terminal Avenue, which contains a portion of the Vancouver SkyTrain line, part of Thorton Park, and a number of low rise light industrial buildings. The northern zone is along the northern shore of Vancouver between Dunlevy Avenue and Salsbury Drive. This area contains a large section of the Vancouver port as well as a segment of Powell Street between Glen Drive and Salsbury Drive. The area of Powell Street inside the buffer region consists mainly of low rise industrial and commercial businesses. Powell Street is a relatively high volume road that runs from the Gastown area of Vancouver to East Vancouver, portions of which serve as access points to the ports for large trucks.

Section 5 - Model Results

Three different scenarios were modeled using two basic programs: ArcGIS, and MATLAB. Python Programming Language was used to transfer data between the two programs. In each case different data was used to represent a different scenario to determine which set up would yield the highest reuse potential.

Scenario 1

The first scenario used the discharge permit data obtained from Metro Vancouver to find the potential for direct cascading of water between companies without treatment. The model searches all companies to see which effluent quality and inlet quality requirements match and then finds the most water that can be pumped between companies given a limited amount of electricity. The total volume of water used, wastewater generated and electricity used to pump the wastewater to Iona WWTP for the 102 permitted dischargers is shown in Table 7.

Total Potable Water Usage	Wastewater Generation	Electrical Consumption
5,240,263 m^3/year	4,192,210 m^3/year	688,000 kWh/year

Table 7 – Summary of water usage, wastewater generation and electrical consumption for the 102 permitted dischargers

In this case, the model showed the potential volume of water which could be shared shared via direct cascading to be 133,438m^3/year or 0.37MLD between 18 sink and 11 source industries. Figure 6 shows the sources, sinks, and required infrastructure of scenario one. The length of pipe infrastructure required to transport this water is approximately 16.3km. See Table 8 for a summary of the results.

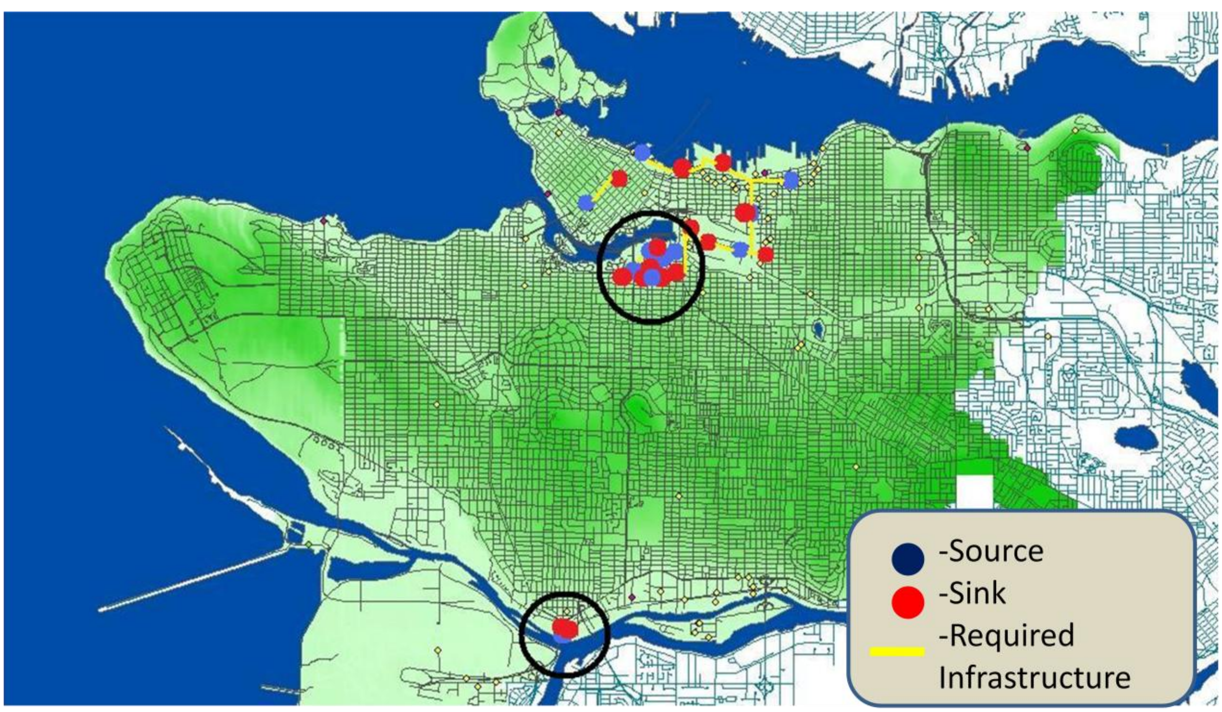

Figure 6 – A view of the entire VSA showing all potential cascading opportunities found by the model. The two circles represent areas of feasible exchange. See Figure 7 for a close up of the upper black circle.

The simulation identified a source and sink from the same company that are under different permits. One of the permits is labelled as `treatment' and the other is labelled as 'bus wash'. According to the data the water discharged under the 'treatment' permit is clean enough to be used as water in the 'bus wash'. As discussed in section 2, reclaimed water used to wash equipment and vehicles can be classified under restricted use and have concentrations below 45mg/L BOD and TSS. If this water was to be utilized for washing busses there would likely have to be further analysis to determine parameters such as pH, coliform count, iron content, and alkalinity. If the results of these analyses are favourable, the company could stand to save \$1530/year (3593m^3/year at a savings of \$0.425/m^3) in water charges in addition to as much as \$1000 on a discharge permit, depending on the type of permit the company requires. It will also save money on the sewerage fees, which, in this case, would be minimal because relatively clean water is being discharged and sewerage charges are based on the weights of BOD and TSS discharged.

It is interesting to note that an earlier study by Mark Jeffery Consultants and Eco-Industrial Solutions identified potential Eco-Industrial Networks (EINs) throughout the lower mainland, two of which were within the study area of this thesis (Eco-Industrial Solutions et al., 2004). One area was identified at Clark Drive/ Hastings Waterfront, which can be seen to have some potential cascading opportunities. The second was the industrial area of Mitchell Island on the north tip of Lulu Island (Richmond). It is evident from the scenario 1 results that there are no potential opportunities for direct cascading between the industries on or around the island. However, this is largely due to the fact that a number of the industries in the area are food producers, which were not included in the first scenario.

This model is very useful at finding potential economical sinks, but there are, however, a number of sinks that are 1-2km from their respective sources. Because infrastructure is required to deliver the water from a source to a sink, this distance would greatly increases the overall length of piping required. The model gives results of this nature because there is still water available for cascading and electricity available to pump it after sinks close to the sources have reached their influent quota. Because of the available water and electricity, the model continues to pump water further and further from the sources, regardless of the lack of economic sense. A change in the electrical constraint to that of a typical city (ie. a city that does not have an elevated water source) was also explored in this scenario. However, increasing the allowable electrical consumption does not increase the number of feasible matches, all of which were identified in the original scenario. In fact, 60% of the electricity can be used to pump 116,000m3/year or 0.32MLD while requiring only 3.0km of pipe. Once below 60% of the initial electrical constraint, the water reuse potential decreases significantly.

% of Energy Quota Used	Water Reuse Potential (m^3/year)	MLD	# of Sinks	# of Sources	Length of Pipe Required	% of Total Water Use
100%	133,438	0.366MLD	17	11	16.3km	2.55
60%	116,000	0.318MLD	11	6	3.2km	2.21
30%	88,750	0.243MLD	8	5	1.7km	1.69

Table 8 - Summary of scenario 1 cascading potential using different electrical constraints

Referring to Figure 6, it can be seen that there are two main areas that contain companies with cascading potential: a group that stretches from just south of the Cambie Street Bridge to the Strathcona area and another group near the north end of the Oak Street Bridge. A close up of the Cambie Street and Strathcona area can be found in Figure 7. The 5 westernmost sinks in this figure represent economical sinks, whereas the 3 easternmost sinks are not economical. The water shared among the 5 economical companies totals 100,714m^3/year and requires 1.4km of piping. Assuming the regular potable water supply costs \$0.85/m^3 and recycled water costs \$0.425/m^3, the savings to the economic sinks would total \$42,800/year. Assuming a pipe installation cost of \$350/m (includes cost of materials) the pipe infrastructure would cost \$490,000. Considering an additional cost of \$5,000 per company to install the proper components at each of the 9 participating companies, the payback period would be approximately 12 years. A more in depth discussion of the economics of water reuse and a satellite WRF can be found in section 6.

As previously stated, water is relatively inexpensive in Vancouver. The source and sink identified in the model that have infrastructure spanning downtown Vancouver from Davie Street to Georgia Street (see Figure 6) have the potential for sharing approximately 4,300m^3 per year, or 0.012MLD. Assuming the regular potable water supply costs \$0.85/m^3 and recycled water costs \$0.425/m^3, this translates into a savings of \$1830/year. According to the basic economic analysis used above, the cost of building 950m of pipe through the heart of downtown Vancouver is \$332,500 plus \$10,000 between the two companies for parts. With a payback period of 187 years, the cost alone far exceeds the savings incurred by the company purchasing the recycled water. In this case, the water cascading is not supported by the economics and the sharing would be deemed infeasible. There are a number of factors such as population density, traffic levels, road uses, maintenance, and existing utilities that are not taken into account in the model that play large roles in the feasibility of infrastructure implementation. In the case of somewhere like the downtown area, these factors will drastically increase the price of installation and O&M. At this stage of the model development, most of these factors have to be taken into account manually.

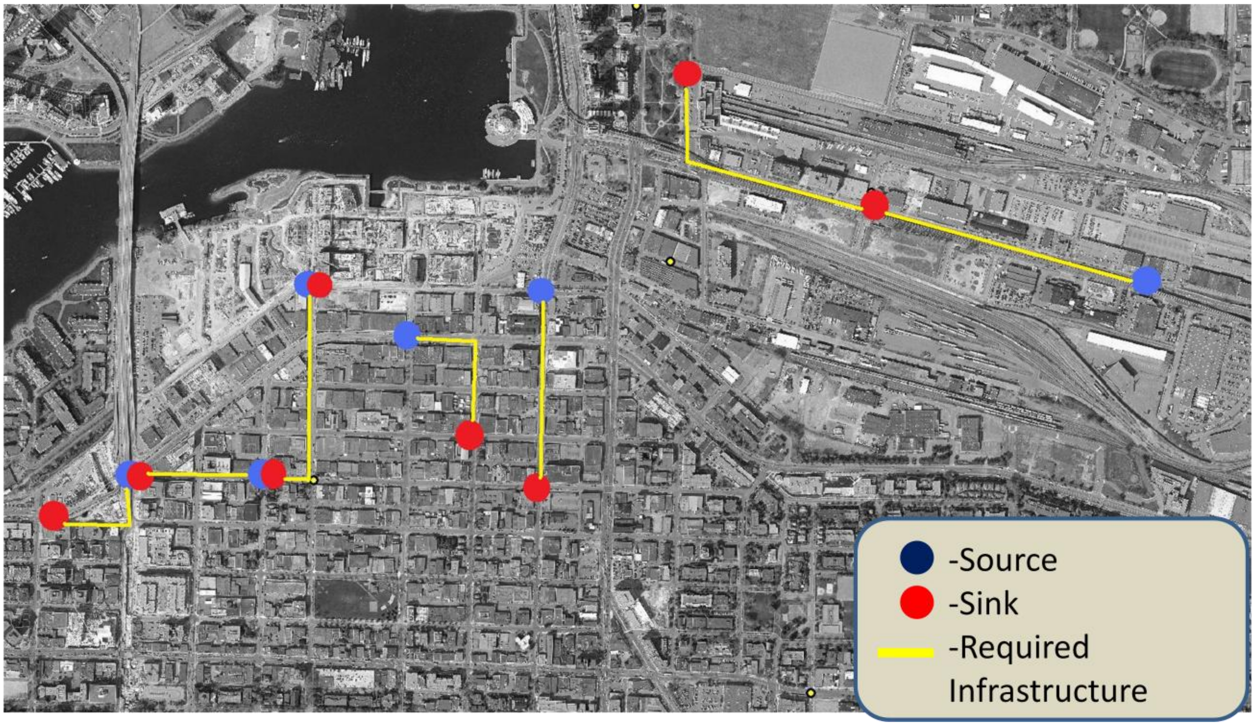

Figure 7- A close up view of a group of potential sources and sinks that are feasible. For reference purposes, the Cambie Street Bridge can be seen in the top left of the photograph.

Scenario 2

The second scenario is similar to the first scenario in that it searches for direct cascading possibilities; however the second scenario also searches for the potential water reuse using water from a satellite WRF. In this scenario, all companies have the potential to receive treated water from the WRF or directly from another industry without treatment. To cut down on the required computation, a number of the companies far away from the potential treatment plant locations, such as the southern group of companies, are removed when computing reuse potential. Instead of 102 companies, 42 companies located greater than 3 km away from the nearest treatment plant or having insignificant water usage (under 10m^3/year) were not used, resulting in 60 companies being considered in the simulation. The 42 companies that were not considered do not have potential for cascading or receiving water from the WRF due to prohibitive infrastructure and pumping costs.

Although 42 companies were removed from the model when calculating reuse potential for the second scenario, the water that was directly cascaded amongst these companies in scenario 1 was included when tabulating the final results of the second scenario. The electricity required to pump water between the southern companies was subtracted from the total used in the optimization and the volume of water shared was added to the scenario 2 total. This was not performed for the northern group of companies because they were all included in the second scenario optimization.

To model a WWTP, a point is added to the GIS map and it is treated like any other company in the model except that its influent requirements are set high enough such that it would be a potential sink for all dischargers (i.e. influent BOD and TSS requirements are both 9999mg/L) and the treated water quality can be modified by simply changing the discharge characteristics. By putting in a centrally located WRF, there is a source of clean, reclaimed water much closer to a number of companies, as compared to the first scenario. This results in a much more efficient use of pumping and a reduced infrastructure cost. The electrical requirement to get effluent from the companies to the Centennial and Stewart WRFs is negligible because of the WRF's low elevation and location relative to the trunk sewer. The Powell street treatment plant location has a slightly higher elevation and it slightly further away from the trunk sewer and as a result uses less electricity to pump the treated water back to the companies (ie the electrical constraint is lowered).

Initially, the model proposed to determine how changing the level of treatment would change the usage potential and a relationship between treatment level versus reuse potential was expected. However, it was soon apparent that the potential for water reuse among industries was significantly higher if the water was cleaned to <10mg/L for both BOD and TSS when compared to water treated to 45mg/L. For reference, the maximum amount of water that can be recycled at 45mg/L BOD and TSS is 678,111m^3/year and at 10mg/L BOD and TSS the potential for water reuse increases to 3,978,869m^3/year. In both scenarios, however, the radius of the distribution area is approximately 1km for all WRFs. See Figure 8.

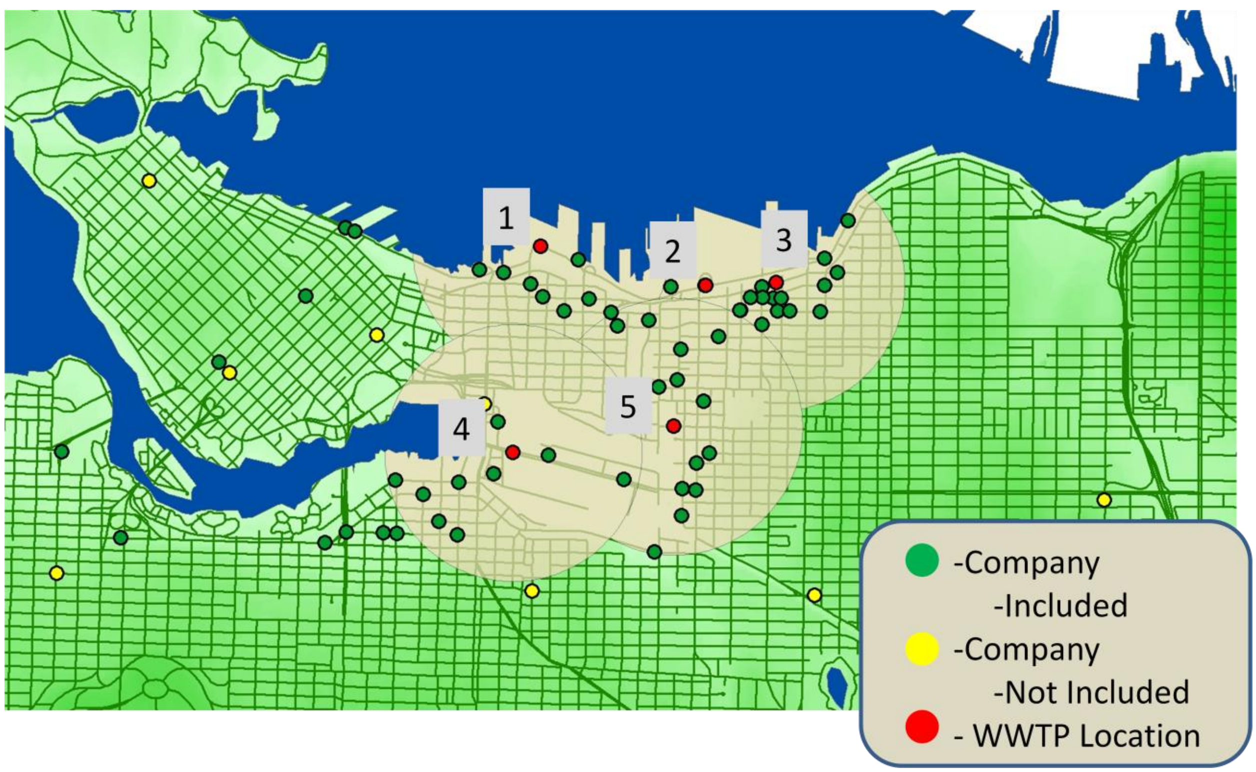

Figure 8 –The locations of all companies included in the second scenario, the five satellite treatment plant locations and a 1km buffer around each WRF representing the approximate distribution limits of the reclaimed water. 1 – Centennial, 2 – Stewart, 3 – Powell, 4 – Terminal, 5 - Williams

The results of the second scenario are summarized in Table 9. They show that the Powell Street WRF has, by far, the greatest potential for the industrial recycling of water. The two locations with the lowest potential for water reuse are the Centennial and Terminal locations. Referring to Figure 8, this is not surprising as there are relatively few companies in close proximity to the WRF, thus greater water pumping would be required. The opposite is true for the Powell street location, which has a large group of companies west of the WRF. Due to the large variation of company water usage, the number of companies within proximity of the WRF alone does not give an accurate estimate of the total reclaimed water usage. This can be seen in the second scenario as Williams WRF, the location with the second largest water reuse potential, has 29 sinks and 6 sources and Powell, the highest potential usage, has only 23 sinks and 10 sources.

WWTP	Reuse Potential (m^3/year)	MLD	# of Sinks	# of Sources	Water Use/Sink (m3/year)	% of Total Water Use
Centennial	251,013	0.688	17	12	14,765	4.8
Stewart	370,065	1.014	18	8	20,559	7.1
Powell	613,808	1.682	23	10	26,687	11.7
Williams	434,799	1.191	29	6	14,993	8.3
Terminal	265,822	0.728	20	11	13,291	5.1

Table 9 – Summary of scenario 2 results for all treatment plant locations.

There are some obvious advantages to having treatment plant locations along the northern shore of Vancouver. Namely, proximity to the trunk sewer and to a water discharge location. There are, however, some notable drawbacks. As previously mentioned, the Stewart and Centennial locations are on Port land, which is strictly regulated and protected by the Vancouver Port Authority. Furthermore, referring to the 1km radii around each of the WRFs in Figure 8, it is evident that although the locations are along the water, a significant amount of reuse potential is lost due to the lack of developed land. Proximity is of great importance because of infrastructure requirements and pumping costs, and with water surrounding the majority of the treatment plant, the reclaimed water must be pumped to further areas, thus increasing costs. If the plant is indeed built on Port land, it would be prudent for studies to be undertaken to find additional uses for both heat and water. Water uses should not be difficult as The Vancouver Port Authority was the fourteenth largest water user in Vancouver in 2008.

Scenario 3

Unlike the first two scenarios that only incorporate water users with discharge permits, the third and final model incorporates any metered water user that consumes over 100m^3/year of water in the proximity of any of the five WRFs, which also includes the 60 permitted dischargers from the first two scenarios. 16 parks were also included in addition to the 2,265 metered water users and proposed WRF for a total of 2,282 points on the GIS map. The 2,265 metered water users consumed a total 9,810,029m^3 in 2008. Using the water consumption data summarized in Table 6, a total reuse potential of 4,674,004m^3 was identified, which represents 47.6% of the area's total water consumption. The potential for reuse using restricted water was only 806,896m^3, approximately 1/6th of the potential when using unrestricted water. As in the case of the first two scenarios, the demand for restricted water was not nearly enough to justify distribution costs and was not simulated in the model.

Due to the number of water users involved in this scenario, the Python code used in the first scenario would generate an extremely large amount of data, which would require far too much memory for a personal computer. To avoid this situation, a different algorithm was implemented to determine the potential for water sharing. When considering the 2,282 metered water users, the new algorithm does not look for sharing *between* users (direct cascading) because this would mean having to store $2{,}282^2$ potential sharing opportunities. Additionally, the effluent quality data does not exist and collecting BOD and TSS samples from 2,265 water users would be logistically challenging. Instead, the algorithm looks only at the potential for sharing between the WRF and water users. This assumption can be made because most metered water users in this case do not use enough water to economically cascade and the vast majority produce domestic wastewater that is not suitable to be shared without first being treated to acceptable levels. Nearly all water users that produce clean water or consume significant quantities of water were taken into account in the first two scenarios.

The results of the third scenario are summarized in Table 10. As in scenario 2, the Powell Street WRF had the highest potential for water reuse with 969,200m^3/year (2.66MLD). The other four WRFs, however, were quite different in their respective reclaimed water use potential. The Stewart Street WRF is a close second with 910,300 m^3/year (2.49MLD) reuse potential but has a 200m smaller distribution radius and a significantly higher average water usage per metered property. A smaller area of distribution would result in less required infrastructure and would require less pumping. The location with the highest average water consumption per user is by far the Terminal Avenue WRF. This is mostly due to the fact that the total number of sinks is much lower than any other WRF location because of its location, which contains large areas of green space, railway, road, and other paved areas. Furthermore, the Powell Street and Williams Street locations are both on the edge of the buffered industrial zone and are much closer to higher density residential areas where large numbers of small water users are located. The result is a larger number of water users and lower average water use, which costs more for infrastructure and pumping.

WRF Name	Reuse Potential (m^3/year)	MLD	# of Sinks	Distribution Radius (m)	Water Use/Sink (m^3/year)
Centennial	791,300	2.17	419	1,000	1,890
Stewart	910,300	2.49	404	1,000	2,250
Powell	969,200	2.66	554	1,200	1,750
Williams	655,600	1.80	566	1,100	1,160
Terminal	674,400	1.85	141	800	4,780

Table 10 – A summary of the results from the third scenario. The distribution radius is the maximum distance water is distributed from the WRF.

Powell Street's 1,200m distribution radius and Terminal Avenue's 800m distribution radius are averages of non circular distribution patterns. The Powell Street WRF distributes water to users 600m away in some directions and as far as 1500m in other directions. Part of the reason the Powell WRF has a larger radius of distribution in certain directions is that it is elevated 8m above sea level, while the others are 2 or 3m above sea level. This extra 5 to 6m of elevation reduces the pumping required to transport water in downhill directions. However, this number is slightly compromised because the Powell WRF is not directly on the trunk sewer and extra pumping will be required to get transfer wastewater into the WRF when compared to the other 4 WRFs that are located directly adjacent to VSA trunk sewers.

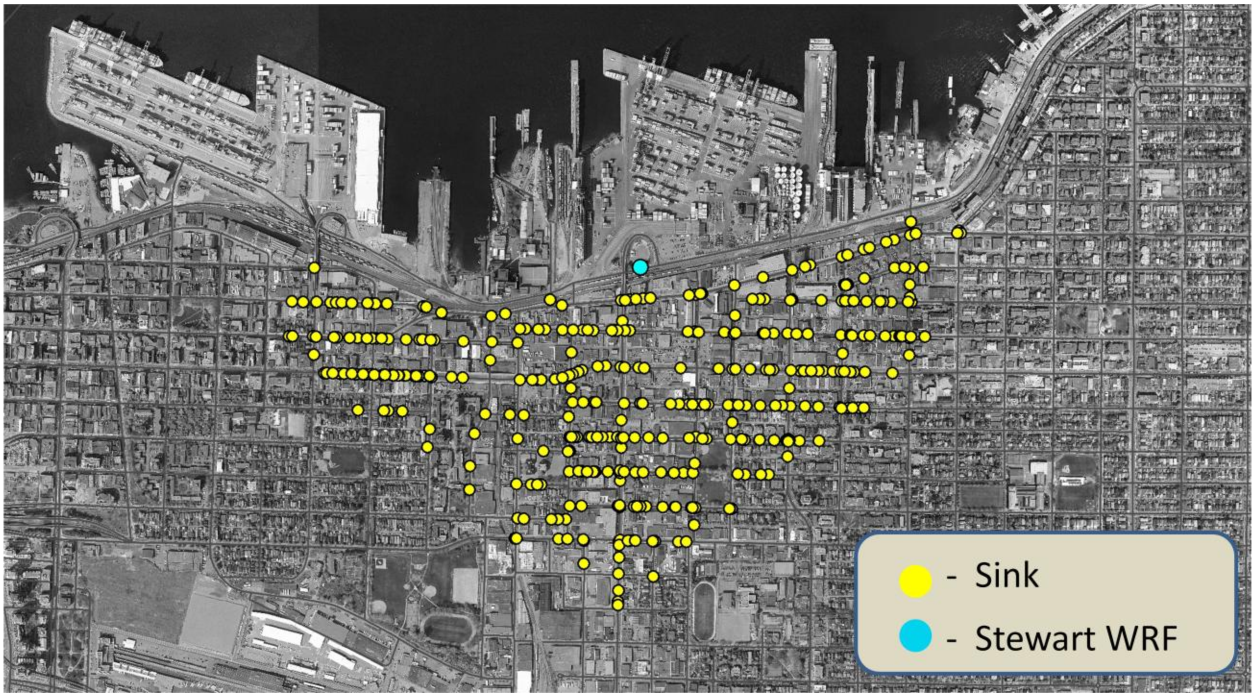

Figure 9 – The sink distribution pattern surrounding the Stewart WRF

It should be noted that there are likely a large number of water users within the distributions radii that are not metered and therefore not taken into account by the model. The City of Vancouver does not monitor single family dwellings that are less than a half acre, so there is a high probability that many of the distribution radii are significantly smaller because of the extra water pumped to residential users for things like toilet flushing and landscape irrigation during the dry months. Although the average water use per user would be smaller, there would likely be enough to modify the results. The decrease in distribution radii and increase in number of users results in a higher density of reuse potential and reduced cost of construction and implementation.

In the first two scenarios, to determine feasible water exchanges the model tested each possible pair of water users to determine whether or not the source facility's water met the influent requirements of the destination (sink) facility. Consequently, 10,404 potential combinations were evaluated in the first scenario because there were 102 industries. Slightly modifying the third scenario, the water shared between the economic sinks from the first scenario was quantified and incorporated into the totals of the third scenario. Table 11 presents a combination of the third scenario and the economically cascaded water from the first scenario. The only difference between this scenario variation, computationally speaking, is that the electrical constraint in the MATLAB script is changed before the optimization is run; this reduces the electricity available to pump treated water from the reclamation facility by the amount needed to pump water between the economical sinks in the first scenario. Once the reduced totals from the modified scenario 3 are calculated, 100,714m^3 of water from the 8 economically viable sinks in the first scenario is added to the final recycle potential and a new total is calculated. Figure 9 shows the potential sinks for the Terminal Avenue WRF as well as the economic sinks from the first scenario. The southern economic cascading region is not shown because of its location relative to the northern economic sinks and the WRF. Showing all areas of reuse would compromise the resolution needed to properly display individual user locations.

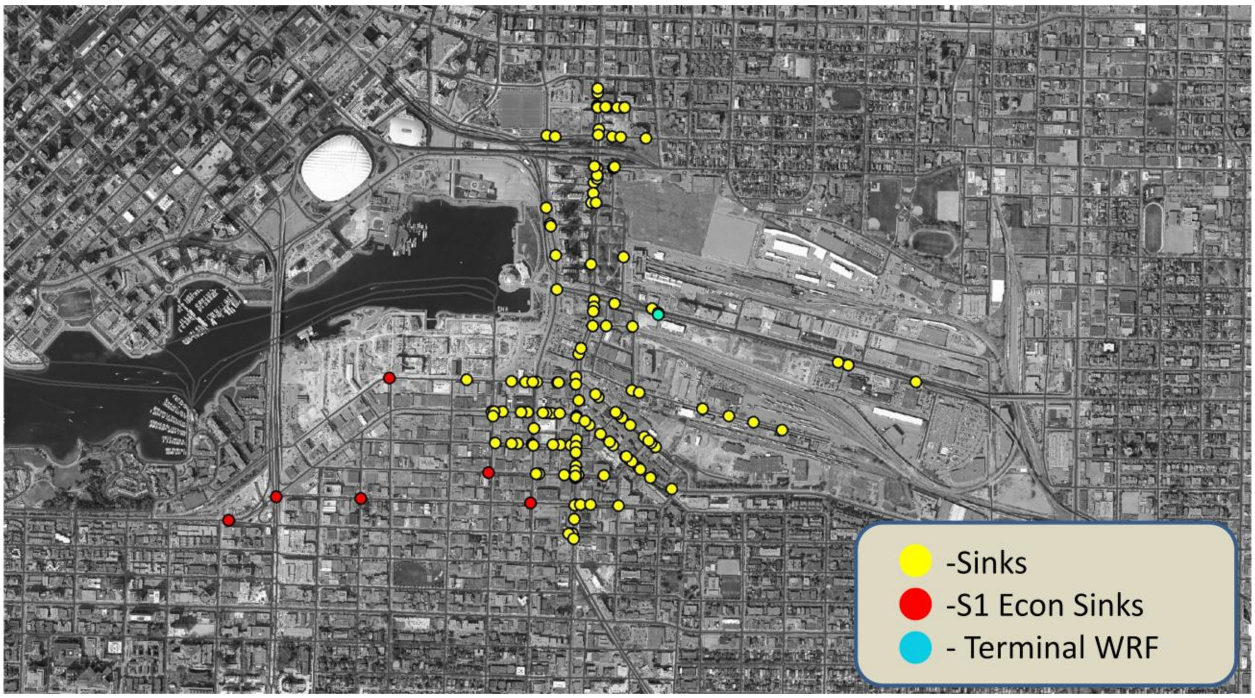

Figure 10 – Terminal Avenue Water Reclamation Facility, potential sinks and the northern economic sinks from scenario one.

It should be noted that although the Terminal Avenue WRF is located relatively close to the northern area of economic cascading potential, none of the cascading companies from the first scenario are sinks in the third scenario, so the Terminal Avenue recycle potential was treated the same as the other treatment plant locations. Figure 10 shows that the economic sinks begin just outside of the Terminal Avenue distribution area.

The modification to include the scenario 1 economic sinks tightens the electrical constraint by 88,278KWh, which reduces the potential for reclaimed water distribution. On the other hand, the volume cascaded in the economic areas, 100,714m^3/year, is added to each total. The result is an average increase of 34,420m^3/year across all 5 WFSs, which varies between 42,800m^3/year at Powell Street and 25,600m^3/year at Terminal Avenue. The relative amounts of reuse potential stayed the same with the addition of the 8 economic sinks. However, despite the addition of 8 sinks, the decrease in the total number of sinks varied between 16 and 81, and averaged 42 across the 5 WRFs. Assuming a uniform distribution of water users and a circular distribution area, the largest reduction in the number of sinks, 81 at the Stewart WRF, would reduce the distribution radius by 106m, which corresponds to a 20% reduction in distribution area. The smallest reduction in distribution radius is 19m at Centennial Avenue and the average reduction in the distribution radius is 56m.

WRF Name	Reuse Potential (m^3/year)	MLD	# of Sinks	Reuse/Sink (m^3/year)	Portion of total water use (%)	Portion of reuse potential (%)
Centennial	828,000	2.27	403	2,055	8	18
Stewart	942,000	2.58	323	2,916	10	20
Powell	1,013,000	2.78	496	2,042	10	22
Williams	692,000	1.9	526	1,316	7	15
Terminal	701,000	1.92	124	5,653	7	15

Table 11 – Summary of the potential water reuse opportunities for all 5 water reclamation facility locations and amount relative to the total water use and total potential water reuse volume.

The largest potential for water reuse given the electrical constraint is seen in this final modification of Scenario 3 and is summarized in Table 11. These results represent the maximum water reuse potential in Vancouver if direct cascading were to occur in areas that have been deemed economically feasible and if a satellite treatment plant was built to supply a section of the city with reclaimed water. In other words, the reuse potentials in Table 11 are a theoretical maximum volume of water reuse that Vancouver can hope to achieve given its current layout. It is evident that although there are some potentially economical direct cascading opportunities between industries, effluent quality and required influent quality is the major barrier limiting the direct cascading of wastewater.

Section 6 – Economics, Liability, and Risk

Economics

The cost per cubic meter of water in each scenario was calculated to provide a quantitative economic comparison, the results of which can be found Figure 11. The length of pipe required to service all of the sinks identified in the third scenario ranges from approximately 20-35km. This is not a realistic scenario because it is unlikely that pipes would be built to provide reclaimed water to many of the small sinks. A fourth scenario was added to calculate the unit cost of water when only the users along the supply pipes of the industrial sinks identified in scenario two are considered. In other words, the same pipe network as scenario two was considered and only the commercial, residential and institutional sinks along these pipes are supplied with reclaimed water.

In this rough cost estimate, the cost of piping, electricity and a WRF was taken into account. The cost of electricity was assumed to be $0.0672 per kWh and the electrical costs over a five year period were included in the calculation. The cost of piping was assumed to be $350/m and the cost of a small WRF was assumed to be $5,000,000.

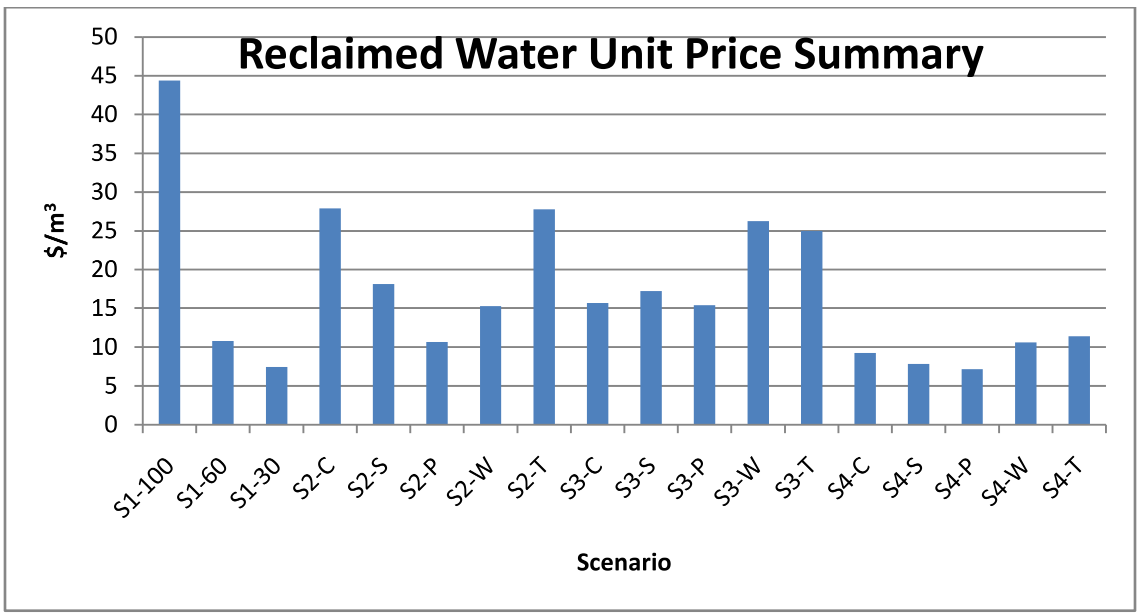

Figure 11 – Unit price of water for each scenario. S1-30,60, and 100 represents the first scenario that used 30%, 60% and 100% of the electrical constraint. S1, S2, S3 and S4 stand for the first, second, third, and fourth scenarios, respectively. C, S, P, W, and T stand for the Centennial, Stewart, Powell, Williams and Terminal wastewater treatment plant locations. For example, S2-P stands for the second scenario when the WRF is located at Powell Street.

Figure 11 shows that the cheapest options are most often encountered in the fourth scenario. Also, the first scenario that only uses 30% of the electrical constraint has a unit price that competes with the fourth scenario. This first scenario also has the added bonus of requiring the least infrastructure of any scenario in this thesis.

Water reuse is a long term undertaking. However, in this thesis there are two different scenarios that represent very different time frames: direct cascading and satellite treatment. When dealing with individual companies, time frames become much smaller because changes within businesses tend to be much more frequent and dramatic compared to the time frame of an entire city. In the case of a satellite treatment facility, a large investment in infrastructure is required and only through strategic planning can it become a reality. In an economy that often demands fast returns, water reclamation is difficult to justify without considering at long term forecasts. From the results presented in the previous section it can be seen that a significantly larger potential for water reuse exists with a satellite treatment facility compared to direct cascading between industries because of water quality constraints. If Vancouver is looking to implement water reuse, a long term plan involving a satellite treatment plant would be the best way to achieve this.

The cost of wastewater reuse consists of two components: capital cost and operating and maintenance (O&M) cost. Capital cost is a function of depreciation, interest and replacement cost, whereas O&M is subject to labour, maintenance, and materials. The City of Vancouver currently uses a $1000/m estimate to budget for their water main construction (Wong, 2010). The cost of adding an additional pipe into the same trench, however, is much less. Based on Stano (2008), the cost of installing infrastructure trenches and associated municipal piping is assumed to be approximately $350/m with an additional cost of $5,000 incurred by each participating industry to install the required piping components to handle the second water supply on site. Other considerations that need to be taken into account when performing an economic analysis for a reclaimed water distribution system are sizing and cost of a chlorine contact chamber, equalization storage operation and maintenance, the gross annual revenue from the sale of the water and the lost revenues from the sale of treated water, and the cost of pump motors. For rough cost estimation, $350/m is a good starting point.

Building a water reclamation plant is a costly undertaking, but its benefits can be enticing, particularly when faced with the having to upgrade a sewer or water distribution system within a major city. The satellite treatment plant will not pay for itself with revenues from water sales or with the money saved from reducing water production at the Seymour Capilano filtration plant but instead, will be made worthwhile by means of social and environmental benefits combined with steps to mitigate implementation costs. These costs include laying an extra reclaimed water pipe at the same time as scheduled upgrades of sanitary mains, implementation of policy that requires dual distribution systems in new buildings and optimizing the location and process at the new satellite facility. Centralized wastewater reuse does not have the nearly the same social and environmental benefits and most of the cost mitigating measures are not available.

Adding complexity to the economic equation are the changing water and sewer prices. As of 2010, the City of Vancouver purchases water from Metro Vancouver for $0.56/m^3$ during the peak months (June-September) and for $0.45/m^3$ the rest of the year. The City then sells the water at a profit of $0.29 and $0.40/m^3$ during the summer peak season and off peak season, respectively. Vancouver’s 2010 sewer rate for residential users is $0.5156/m^3$, which is based on 80% of metered water usage. Vancouver’s 2010 flat fee for a single family dwelling is $417 for water and $227 for sewer. The wholesale price at which Metro Vancouver sells its water has increased from about $0.22/m^3$ in 2004 (there were no peak and non-peak rates at this time) and has recently been forecasted to sell for $0.69/m^3$ and $0.88/m^3$ for non-peak and peak, respectively, by 2014 (Metro Vancouver, 2010 (1)). Despite this drastic increase in water prices, Vancouver's water is still inexpensive compared to similar sized cities such as Seattle ($1.23/m^3), Calgary ($1.25/m^3), Edmonton ($1.56/m^3), and Toronto ($1.89/m^3). Based on simple payback, Figure 12 shows the relationship between distance between cascading companies and the volume of water needed to obtain a five year payback period.

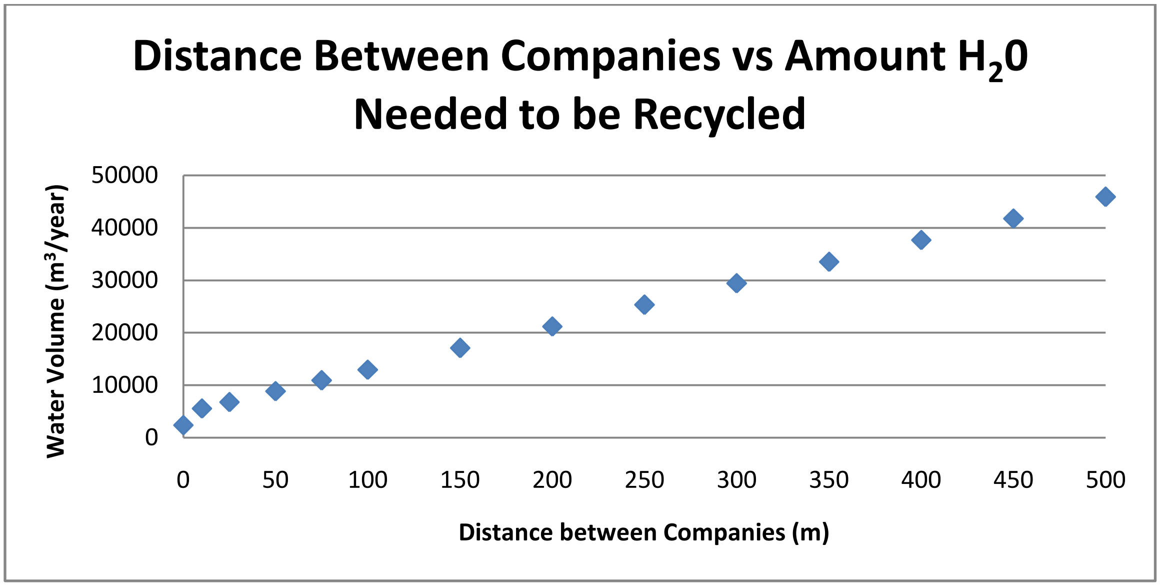

Figure 12 – At a potable water cost of $0.85/m^3, the volume of water needed to be sold in order to obtain five year payback period for a given distance between source and sink

Opportunity for implementation of water reuse in new developments is considerably greater than retrofitting an older building, particularly when the use of reclaimed water is incorporated into the planning stages. The infrastructure needed for the distribution of reclaimed water is best incorporated into new developments during the design and implementation phases (Gikas & Tchobanoglous, 2009). When designing the reclaimed water facilities for new developments, the vicinity's wastewater production should be taken into account with the objective of matching the production of reclaimed water with the demand for reclaimed water. This way, reclamation facility storage requirements can be minimized and costs can be drastically reduced.

As technology improves and water becomes an increasingly valuable commodity, water reuse will become more economically viable in a larger variety of situations. According to Viessman & Hammer (2005), the average cost of treating water in the United States in 2004 was $0.53/m^3. As treatment technologies such as membrane bioreactors and advanced oxidation become increasingly cost effective, the cost gap between potable water and reclaimed water will decrease. In addition to technology, infrastructure and planning should also improve to increase the feasibility of reclaimed water. Millions of dollars per year in Vancouver alone are being spent on upgrading aging municipal infrastructure that has an average age of 56 years and leaks an estimated 11% of the potable water purchased from Metro Vancouver (Metro Vancouver, 2008).

When speaking to Vancouver companies, there was a noticeable reluctance to the idea of reusing water. Water reuse is much less common in Canada compared to a number of other countries such as the

United States and Australia (Exall, 2004). It is apparent that the implementation of reuse cannot happen overnight and that the general public will need time to get used to the idea of using reclaimed water. Additionally, there needs to be adequate economic incentive from government in the form of tax credits or grants. At this point, there may be a number of water reducing methods that may be simpler and cheaper than recycling water from a satellite water reclamation facility. Some methods may be as simple as increasing the cost of water to reflect the actual cost of treatment and distribution or to implement a universal water metering scheme. For example, the use of decentralized treatment systems, which are small treatment systems that are not connected the main sewage collection system, could be used to reduce the cost of infrastructure in areas that are far away from existing sources of reclaimed water.

A paper by Chu et al., 2004, used linear constraints to model economic constraints in water reuse. They were able to do a sensitivity analysis on how changing water prices would affect water reuse in the different sectors. In many areas of China the price of water for use in a thermal power plant is almost negligible and very little water is reused in the sector as a result. If prices of water reflected its actual value, reclaimed water use increases six fold. A similar situation is seen in the agricultural sector where increases in water prices cause a non-linear effect on the water reuse and an increase of approximately 0.2 RMB Yuan/m^3 (approximately $0.03 CAD) caused an increase in agricultural water reuse of 1400% (Chu et al, 2004). This example provides a useful tool in analyzing the future potential for water reuse and how changes in water and sewerage price in some or all users would promote different water usage incentives.

Regardless of the case, the economics surrounding water reuse projects are difficult to accurately predict and are heavily influenced by a number of variables such as the nature of effluent being treated, the type of treatment used and the required effluent quality (Asano et al., 2007). However, in most cases heat recovery can be counted on to reduce the cost of water per cubic meter (Roeleveld and Maaskant, 1999). The economics may be modified if the heat recovery is in conjunction with water reclamation, but the business case for a wastewater heat recovery project must include financing costs and sources, a customer base, and an ownership structure. Ownership and financing are closely related in most arrangements and governments will often be included. Municipalities will often have access to low-cost financing compared to privately financed projects. In addition, energy pricing must be attractive enough to pull customers away from conventional energy sources. Based on current energy prices, this means the total cost of providing recovered wastewater heat should be in the $10-$15/GJ range (Johnston *et al*., 2009).

An aspect of the satellite WRF that drastically affects its costs is the size of the facility. Some factors that affect the size of the plant aside from water reuse potential can be wastewater availability, energy recovery potential and potential for energy distribution, available land, economic/funding considerations and the ultimate goal of the treatment plant (Gikas and Tchobanoglous, 2009). For example, if the goal of a satellite facility is to take pressure off of the Iona WWTP, a minimum size representing approximately 10% (60MLD) of Iona’s daily flow would need to be constructed. However, if the plant is built purely in the interest of resource recovery, a balance between the facility size and forecasted reclaimed water and heat demands would have to be found. An in depth quantification of water demand would have to be done as well as an in depth analysis of the energy and heat demand in the chosen area. The technique presented in this thesis could be used as a rough, high level estimation of an area's potential for water reuse.

To reiterate, the most important economic message that can be taken from this section is that water reuse on the scale that this thesis deals with is a long term commitment. It would require extensive planning and will not make short term economic sense because the infrastructure required would be costly and likely take decades to fully implement (Asano et al., 2007). Although small scale reuse is feasible when direct cascading between industries is considered, a larger commitment over a longer term is needed to establish a sustainable and reliable water reuse system. Given a longer time frame, proper planning, and the social and environmental benefits of water reuse, it is very realistic that water reuse can be economically feasible.

Risk and Liability

Although the technology to treat water to any level is available, guarantees that nothing will go wrong in a system as complex as a reclaimed water system are impossible to make (Asano et al, 2007). This statement is even more applicable when dealing with a satellite WRF because implementation in urban setting is a relatively new concept and the development of a proven track record is ongoing. This following section outlines some of the risks and liabilities associated with water reuse projects.

Albeit low, there is an inherent health, liability, and financial risk associated with using reclaimed water that needs to be considered in the overall feasibility assessment. The main objective of a risk assessment is to identify the hazards and to evaluate available scientific information to decide whether a hazard exists and to characterise the associated risks (Huertas et al., 2008). It is much more proactive to assess the potential hazards as opposed to reacting when a problem occurs. The most effective way to ensure that reclaimed water is used safely is to become aware of the types of hazards that may impact reclaimed water and adopt appropriate strategies to manage these hazards. An example concerning industrial water reuse is minimizing organic carbon to protect the anti-corrosion layer on copper pipes so that the risk of pipe breakage and resultant human exposure is minimized.

There are certain liabilities and risks associated with cascading water from industry to industry. Due to the policies imposed by the municipal sewage regulation and the liability associated with microbial contamination as a result of using recycled water in food processing plants, food processing industries were not included as potential sinks of recycled water and their water inputs were set to zero. This led to only 50 of the 102 permitted water users to be included in the initial scenario. The MSR authorizes the use of reclaimed water for two different water quality standards, referred to as category 1 and category 2 (see section 2). The intent is to identify two different qualities of treated water for various uses. One issue that arises when directly cascading water between industries is that MSR requires water to be *treated* to a minimum standard before it can be reused. This would avoid shocks to industrial processes or liability associated with reduced equipment performance or even failure associated with reclaimed water usage. Although a company may consistently produce effluent of a certain quality, it is prudent to implement safeguards against the case where a system malfunction produces effluent of poor quality. Problems may also arise when a company supplying potable water moves locations or goes out of business while still under contract to supply reclaimed water.

The model does not require the user to specify how the water is treated and it does not take into account variation in a company's effluent quality. It is assumed that all water coming from a source is of a constant quality, which is not the case. It is likely that a treatment plant can consistently meet objective goals and treat water to a minimum of the required quality. The effluent concentrations will usually be better than the minimum standard and storage is built for the case that effluent does not meet standards. Conversely, water sources that pump their water directly to sinks are much more likely to experience fluctuations in their effluent quality. This is in part because companies have had little reason to mitigate these fluctuations in the past and would likely have to invest capital in treatment technology to minimize the fluctuations (Eco Industrial Solutions et al., 2004). Therefore there is an inherent risk that must be taken into consideration when water is taken directly from another company as opposed to a WRF.

There may also be liability associated with the location of the treatment plant. The 2008 Land Use Plan set out by the Vancouver Fraser Port Authority states that the general land use policy direction for the port area is to optimize the current land use by "encouraging land use efficiency and operational productivity; and ensuring that sufficient and appropriate land is available for future port growth opportunities by acquiring, creating or exchanging lands as needed" (Vancouver Frasier Port Authority, 2008). There are a variety of technologies that can significantly reduce the footprint of a water reclamation facility without compromising the quality of the end product (O'Connor, et al., 2008). Space is very limited at the Fraser Port and fitting in a relatively small treatment plant may only be a possibility once the potential benefits of a cheap and reliable water supply, sewer discharge costs, and a significant source of heat energy are realized and effectively communicated to port authorities.

Section 7 - Discussion

Like all other large scale projects, successes and failures of similar past projects should be analyzed. There are a large host of reasons why a water reuse project in Vancouver may not be successfully implemented. Seven major feasibility criteria are identified in a planning analysis by Mills and Asano (1998) to determine a project's feasibility, which include engineering feasibility, economics (market feasibility), financial and institutional feasibility, environmental impact, social impact and public acceptance. Each of these have varying importance depending on the nature of the project and the specific location. As important as each of these 7 criteria are, there are still additional factors that have been identified as being crucial in successful implementation. Namely, Hermanowicz *et al*. (2001) looked at a Californian case study of water reuse implementation and identified accurate demand analysis and early connections to large customers as important factors. Stability and reliability of large customers is also important in projecting demands and maintaining economies of scale at the treatment facility. Furthermore, an assessment of the effects of the water treatment facility on the surrounding environment would have to be performed.

Economic Impacts

Having a water reclamation facility in close proximity to a commercial, institutional, or residential building is likely to reduce the value of surrounding property. Ideally, most of the issues with aesthetics and smell can be minimized by proper design, but there still exists a stigma surrounding a waste water treatment plant (Hartley, 2005). Much of the required infrastructure, including trunk sewer, force main, and gravity sewer for wastewater conveyance to and from the site already exists in the area, which greatly reduces infrastructure costs. However, the construction of pipelines could reduce access to surrounding areas, potentially decreasing the number of customers for the local businesses. A potential way of minimizing some of the impacts would be to utilize the construction of the separated sewer system by installing some of recycled water distribution pipes at the same time (Revelle and McGarity, 1997).

By mining water from the trunk sewer, the satellite facility will reduce the volume of water flowing through the trunk sewer and the velocity of the remaining water in the pipe will therefore decrease. It has been speculated that the decrease in velocity may result in an increase in settling, which can lead to odours, plugging, and an increase in maintenance costs (Andoh, 2004). Depending on the set up of the satellite facility, the solids extracted from the wastewater during the treatment may be discharged back into the trunk sewer, further exacerbating the problem of settling and increased maintenance costs. However, municipal wastewater typically contains about 1% solids and 99% water (Andoh, 2004), and therefore a large portion of the pumping requirements are used to pump water. Decreasing water volume by 50% will only increase the solids concentration from 1 to 2%. The volume of water to be extracted from the trunk will vary depending on the size of the treatment plant. As much as 50MLD will be flowing through some of the sewer mains and strategic discharge of the solids may minimize some of this problem.

According to the National Round Table on the Environment and Economy, unmet water and wastewater infrastructure needs in Canada were estimated to cost $38-49 billion in 1996, and capital costs for the following 20 years will be in the order of $70-90 billion (Environment Canada, 2010). The U.S. Environmental Protection Agency estimates an investment need of roughly $300 billion through to 2019 for wastewater systems, which includes upgrades to existing and new wastewater treatment systems and existing wastewater collection systems. The amount of North American Infrastructure that is required over the next 10 to 20 years is staggering. If the potential benefits of satellite treatment are realized, there stands to be a considerable amount of money saved, a vast amount of water conserved, and a significant move towards sustainable water practices.

Environmental Impacts

When building a WWTP, the land must be cleared of vegetation to make way for construction. Because the area is already fully developed, it contains minimal wildlife habitat and other ecological value. The increase in truck traffic and the associated noise and dust would be negligible as the port is very close and already receives a large number of transport trucks that access the area via designated truck routes (Vancouver Frasier Port Authority, 2008). If the increase in truck traffic proves to be a problem, the screenings and waste solids can be discharged back into the trunk sewer and treated at the Iona WWTP.

Another major point of concern with locating a treatment plant at any location other than the three most northern potential locations, Centennial, Stewart, and Powell, is the impact on Burrard Inlet water quality. The inlet is home to both aquatic life and wildlife, with the tributaries providing much needed habitat for salmonid runs (BC MOE, 2001 (1)). The water body is already under a considerable amount of strain from a number of pollution sources including bulk loading facilities, oil refineries, chemical plants, combined sewer overflows, stormwater discharge, and another WWTP. The addition of another significant point source may cause unrest and be difficult to justify. However, the stringent discharge standards that the reclamation facility would adhere to should ease most of the pollution concerns.

The closest discharge location to the other two proposed locations, Terminal and Williams, is False Creek. A discharge of the proposed volume and nature would be extremely difficult to justify to the city and even harder to the inhabitants of the area. False Creek receives minimal tidal flushing and is in a highly urbanized area with large numbers of people using it for recreational purposes (CBC, 2008). Although the satellite plant would result in a decrease in the total volume of effluent being discharged into the environment, displacing some effluent from a remote area to an area as highly urbanized as False Creek would probably not be acceptable. For this reason, Terminal Avenue and Williams Road locations are considered undesirable locations.

Social Impacts

While the three northern potential site locations make sense both economically and environmentally, social acceptance of water reuse presents a large source of uncertainty. To minimize the impact on surrounding properties, a 200m buffer zone was placed around all land that was zoned for all types of residential, commercial, and historical use. None of the proposed locations fall on bike routes, park land or other recreational areas. The region would offer minimal visual screening until planted vegetation matures but the structure could be designed with anonymity in mind and could easily blend into the surrounding industrial areas. A pond or other ornamental feature may be considered as a potential water use if excess reclaimed water is generated. Obviously, the plant would have to be designed for a highly urbanized area and have to keep aspects like odour control and aesthetics at the forefront of design considerations. Additionally, community involvement would be necessary to provide information to the local community, better the public's perceptions and to serve as a forum for input and feedback (Hartley, 2005).

The majority of the area identified by the buffered map has been previously developed, which should negate potential issues surrounding archaeology, heritage and geotechnical suitability. The port land has an extensive railroad system in place, which can potentially cause complications during the construction due to the increased truck traffic over a limited number of access points to the port. However, this would only be an issue if the satellite plant chooses to deal with solids on site. Security may also be an issue as the port requires a security pass to enter the area. The minimal number of technicians required to run the plant at any given time should minimize this problem.

Triple Bottom Line Analysis for Effluent Reclamation

When assessing the benefits of reusing water, it is all too common to limit the assessment to economic and environmental benefits. Potential social benefits can also be very significant and play a large role in whether or not a project proceeds. Conventional centralized treatment was based on building the treatment plant out of sight and far enough away that nobody would have to see or smell the treatment plant. This encourages the "out of sight out of mind" mentality, which spurs little public involvement (Asano et al, 2007). Satellite style facilities, on the other hand, provide a basis for community involvement whether it is in the form of public gatherings or educational seminars (Hartley, 2005). Much more information regarding sustainability and the benefits of water reuse and recycling will be conveyed to the general public, which can result in higher acceptance rates and open the door for further schemes involving water reuse (Hartley, 2005).

Model Limitations and Future Directions

The model presented in this thesis was used to assess the opportunity for water reuse in the VSA by analyzing wastewater qualities and water requirements as well as constraining the volumes and electricity consumed by pumps. Although the model may give a reasonably accurate assessment, gathering enough data to run the model for the VSA was time intensive and subject to a number of assumptions. There are also a number of ways that the accuracy and usability of this model can be improved. The following section assesses some of the model shortcomings and ways to improve its results.

A major shortcoming of this model is that the only data readily available regarding water permit holders was BOD and TSS concentrations. This is a result of regulations concerning the effluent discharge from Iona WWTP that only take into account BOD and TSS. The MSR regulates a large number of pollutants in addition to BOS and TSS. However, not all companies are required to monitor for these particular constituents (BC MOE 2001). If a constituent is to be included in the model, it is necessary for all or most companies to monitor for that substance. The time and cost associated with sampling hundreds of companies for all potential pollutants is prohibitive.

If planners were to go forward and seriously consider using this model as a decision tool for finding possible water sources or sinks, a more in depth analysis of the effluent water constituents would be needed. For example, when evaluating a water source for makeup to a refinery cooling system, typically the parameters of primary concern are hardness (total and calcium), alkalinity, silica, and total suspended solids. In special situations (such as the use of reclaimed water), a number of other parameters such as ammonia, phosphate, iron, compounds, total dissolved solids, chlorides, microorganisms and organics may also be important (Selby and Helm, 1996). See section 3 for a more in depth description of how these parameters can adversely affect process water. Additionally, low levels of certain impurities can cause equipment operational issues. For example, certain ratios of phosphorus and other constituents can result in the precipitation of a number of cement-like minerals (Armon *et al*., 2002).

If populated with appropriate data, there is no doubt that this model could be very useful to other cities, particularly in larger cities that are considering more than one satellite plant. Multiple WRF would be especially useful if a number of development plans are scheduled for an area. The VSA represents the large end of the spectrum in terms of the size of undertaking and, resultantly, is a very complex system. As a trade off, however, due to the size and urbanized nature of Vancouver, much of the data (road maps, sewer maps, elevation maps and effluent concentrations for a large number of industries) was readily available. If a less urbanized area were to be studied, it is likely that less GIS data and fewer, if any, effluent concentration would be available. Conversely, fewer water users would have to be included in the model and there would likely be more opportunities for landscape and agricultural irrigation, which represent relatively easily accessible sinks for reclaimed water. When analyzing highly urbanized areas, strategically limiting the area of analysis to a small geographic location will be very useful in limiting the required data gathering and subsequent computational requirements.

The earlier version of this model used a much smaller area where geography was less of a constraint. A single industrial cluster was analyzed and there was no company more than 100 meters away from the next closest company. In this thesis, a small number of the results must be set aside due to the required infrastructure costs. Code should be added to the existing algorithm to include payback period by analyzing the distance between companies and the associated cost of infrastructure to determine whether or not there is enough reclaimed water demand such that the payback is within a certain time period. As stated in section 6, the economics are often more complicated than what can be modeled by a relatively simple algorithm. The model would also require constant updating to stay abreast of the current economic conditions. Additionally, there are social and environmental benefits from water reuse that are difficult to economically quantify.

There were a number of recycled water uses that the model did not take into account such as car washing, garden irrigation and air conditioning, firefighting, ornamental use and street cleaning. These factors were excluded in this model because a number of these activities are only implemented for small portions of the year and in some cases not at all. Applying this model to an area with greater agricultural or irrigational needs would greatly simplify the calculations and could drastically increase the reuse potential. Unfortunately, less than 1% of Vancouver's water is used for agricultural purposes and thus could not be taken into account. However, green spaces such as public parks were taken into account.

Possible locations in the lower mainland that may have the potential for agricultural reuse include areas of Richmond, Delta, Pitt Meadows and Langley.

Section 8 - Conclusions

The model, albeit potentially time intensive to set up, can be a very effective tool for a first over quantification of an area's water reuse potential, regardless of the level of urbanization. It is transferable to other cities and, depending on the available data, it may be fairly simple to set up and run. Although most effluent data was limited to BOD and TSS, the results from all three scenarios are still very useful and showcase the model as a valuable planning and analysis tool. Furthermore, methods of improving the results and usability of the model to increase the potential applications are suggested.

In the first scenario, the model looked at direct cascading between industries. With 102 permitted dischargers as data points in the GIS model, 12 sources and 18 sinks were identified to have a potable water savings of 133,400m^3/year and wastewater reduction of 106,800m^3/year. Many of these cascading opportunities, however, were deemed infeasible based on high level economic analysis. Within these potential cascading opportunities, 5 sinks and 4 sources were found to be economical sites for cascading and were identified to have a potential savings of 116,000m^3/year and a wastewater savings of 92,800m^3/year, while using only 60% of the available electricity.

When a satellite treatment plant was added in the second scenario that was modeled, the opportunity for reusing water within the industrial sector was greatly increased by the addition of a steady source of treated wastewater. In this scenario, which looked at the same 102 permitted dischargers from the first scenario, the reuse potential was found to range from 251,013m^3/year to 613,808m^3/year, depending on the location of the satellite WRF. The utility of a satellite WRF was showcased, but its applications were limited because only industrial water users were considered.

The third and final scenario took into account the same 102 points as the first two scenarios but added an addition 2180 points that consisted of parks and metered water users, which are made up of commercial, industrial, institutional, and multifamily users. This way, the infrastructure used to transport water to industries up to 1km away from the satellite WRF can be utilized to transport reclaimed water to other potential users along the way. This scenario saw the opportunity for water reuse jump significantly to 692,000m^3/year to 1,013,000m^3/year, depending on the location of the satellite WRF. The third scenario displayed the utility of the satellite treatment plant more effectively than the second and demonstrated that the demand for reclaimed water in a section of Strathcona to be upwards of 1,000,000m^3/year.

It is evident from the aforementioned results that the location of the satellite WRF significantly impacts the opportunity for water reuse. From an analysis of various economic, environmental, and social factors, combined with the results of the model, the best location for a satellite water treatment facility appears to be in the proximity to the intersection of Powell Street and Salsbury Drive. This area is zoned as industrial with at least 200m of industrial land in all directions. Aesthetics would be a minor issue and a properly designed WRF would minimize odour issues. The area currently receives a high volume of large trucks, so the effect of a slight increase in dust, noise and traffic volume as a result of increased truck traffic would be negligible. Furthermore, a number of large industrial water users are within proximity, limiting the length of piping required. The location is also directly above a trunk sewer, which minimizes the pumping required to transport the wastewater to the satellite facility. Finally, there are a number of appropriately sized vacant lots or parking lots in the area that could be utilized as a WRF site and the absence of a building may reduce the cost of the land.

The results from the three modeled scenarios show that the conventional idea of IE where one industry's waste is used directly by another industry does not yield the greatest potential for water reuse. Rather, when a satellite treatment plant in close proximity to the end user cleans wastewater, a much larger potential for water reuse exists. Although there is significant potential for water reuse in Vancouver, there is still significant potential for Vancouverites to reduce their water consumption by means that are much simpler and cheaper than water reuse. Given the 20-40 year time frame for a water reuse project of this nature to be fully implemented, much of water reclamation opportunity should be re-evaluated through time as industries, businesses, public opinion, and the City of Vancouver continue to evolve.

References

.

Andoh, R.Y.G. (2004). "Why Satellite Treatment Within Collection Systems Makes Sense." Presented at Collection Systems 2004: Innovative Approaches to Collection Systems Management. Milwaukee, Wisconsin, August 8-11.

Angelakis, A.N., Marecos do Monte, M.H.F., Bontoux, L., and Asano, T., (1999)." The Status of Wastewater Reuse Practice in the Mediterranean Basin: Need for Guidlines" Water Research **33**(10): 2201-2217.

Armon, R., Gold, D., Brodsky M. and Oron, G. (2002). "Surface and subsurface irrigation with effluents of different qualities and presence of *Cryptosporidium* oocysts in soil and on crops". Water Science and Technology, **46**(3): 115–122.

Asano, T., Burton, F.L., Leverenz, R., Tchobanoglous, G., (2007). Water Reuse: Issues, Technologies, and Applications. McGraw-Hill, New York.

Bastianian, R. K. (2006). "The future of water reuse." BioCycle, **47**(5): 25-27

BC MOE (2001). Municipal Sewage Regulation - Code of Practice for the Use of Reclaimed Water.

BC MOE (2001) (1). Ambient Water Quality Objectives for Burrard Inlet Coquitlam-Pitt River Area Resource Quality Section, Water Management Branch. Accessed electronically at http://www.env.gov.bc.ca/wat/wq/objectives/burrard/burrard.html on August 8, 2010.

Bennett, A. (2008) "Drinking water: Pathogen removal from water - technologies and techniques" Filtration and Separation, **45(**10): 14-16.

Bolong, N., Ismail, A.F., Salim, M.R., and Matsuura, T. (2009). "A review of the effects of emerging contaminants in wastewater and options for their removal." Desalination **239:** 229–246

Canadian Broadcasting Corporation (2008). False Creek Could Make People Sick: Health Official. Accessed electronically at http://www.cbc.ca/canada/british-columbia/story/2008/07/04/bc-dirty-false-creek.html on November 22, 2010.

Chu, J., Chen, J., Wabg,, C. And Fu, P. (2004). "Wastewater Reuse Potential Analysis: Implications for China's resources management." Water Research **38:** 2746-2756.

Canadian Water and Wastewater Association. **(**1997). Regulatory barriers to on-site water reuse. Report to Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Chieng, S. (2009) Personal communication November 2009. R. Thoren. Vancouver.

DeMarco,C. (2009). Tensions, Tradeoffs and Trophies: Regional Planning in Metro Vancouver. Presentation at the 2009 BC Land Summit, May 20-22, Whistler, BC.

Department of Agriculture Fisheries and Forestry, Australia (2007). Final report on Water use in the food industry.

Division of Pollution Prevention and Environmental Assistance and Division of Water Resources of the N.C. Department of Environment and Natural Resources, and Land-of-Sky Regional Council, (2009). Water efficiency Manual for Commercial, Industrial and Institutional Facilities.

Eco Industrial Solutions, Mark Jeffery Consultants, Kerr Wood Leidal Associates, ECOTEK Ecological Technologies. (2004). Eco-Industrial Network Solutions for Stormwater and Wastewater Management in Greater Vancouver." Report prepared for the GVRD, Policy and Planning Department, Demand Side Management Devision.

Environment Canada (2006). "Municipal Water and Wastewater Survey – Municipal Water Use 2006 Summary Tables"

Environment Canada (2010). Withdrawal Uses. Accessed electronically at http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=851B096C-1#municipal on May 14, 2010.

Environment Canada (2010). "Canadian Climate Normals 1971-2000". Accessed electronically at http://www.climate.weatheroffice.gc.ca/climate_normals/stnselect_e.html on July 29th, 2010.

ESRI (2010). "Overview of Geographic Information Systems" Accessed electronically at http://www.esri.com/what-is-gis/index.html on February 3, 2010.

Exall, K. (2004) "A Review of Water Reuse and Recycling, with Reference to Canadian Practice and Potential: Applications." Water Quality Research Journal of Canada **39**: 13-28.

Exall, K., Marsalek J. and Schaefer K. (2004). A Review of Water Resource and Recycling, with Reference to Canadian Practice and Potential: 1. Incentives and Implementation." Water Quality Research Journal of Canada **39:**(1) 1-12.

FAO (2003) "World agriculture: Towards 2015/2030" Accessed electronically at http://www.fao.org/docrep/005/Y4252E/y4252e00.HTM on September 22, 2009.

Friesen, K. (2008) "Think City, Dream Vancouver: Policy Brief, Water Conservation". Research Paper, Simon Fraser School of Public Policy.

Gelman, S.R., Scott, S. And Davis, H. (1989) "Waste Minimization in the Poultry Processing industry – Process and Water Quality Aspects". Presentation to Misstap Workshop, Waste Minimization for Mississippi Industries, Mississippi State University.

Geng, Y. (2004). "Integrated Water Resources Planning and Management at the Level of an Industrial Park". Dalhousie University, Department of Chemical Engineering. Halifax, Nova Scotia. **PhD Thesis**. 197.

Gikas, P. and Tchobanoglous, G. (2009). "The role of satellite and decentralized strategies in water resources management" Journal of Environmental Management **90:** 144-152

Globalwaterintel (2010). “Summary of Data from the 2008 GWI/OECD Global Water Tariff Survey” Accessed electronically at http://www.globalwaterintel.com/archive/9/9/analysis/world-water-prices-rise-by-67.html on May 29, 2010

Graedel, T.H., Graedel, T. E. and Allenby B. R. (2009). Industrial Ecology and Sustainable Engineering Prentice Hall, New Jersey.

Greater Vernon Water (2006). “Master Plan Water Projects”, Engineering Services, Vernon. Accessed electronically at http://www.greatervernon.ca/index.php?p=2.051 on July 11, 2010.

Hartley, T.W. (2005). “Public Perception and Participation in Water Reuse.” Desalination **187:** 115–126

Hermanowicz, S.W., Sanchez Diaz E. and Coe J. (2001). “Prospects, problems and pitfalls of urban water reuse: a case study”. Water Science and Technology. **43(10):9–16**.

Huertas, H., Salgot, M., Hollender, J., Weber, S., Dott, W., Khan, S., Schafer, A., Messalem, R., Bis, B., Aharoni, A. and Chikurel, H. (2008). “Key Objectives for Water Reuse Concepts.” Desalination. **218:**120-131

Johnston, C., Lindquist, E., Hart, J. And Homenuke, M. (2009). “Four Steps to Recovering Heat Energy from Wastewater”. Watermark Magazine, Summer 2009. 16-18.

Lazarova V., Levine B., Sack J., Cirelli G., Jeffrey P., Muntau H., Salgot M. and Brissaud F. (2001). Role of water reuse for enhancing integrated water management in Europe and Mediterranean countries. Water Science and Technology. **43(10):**25–33.

Leitão, J.P., Matos J.S., Goncalves A.B., and Matos, J.L. (2005). Contribution of Geographic Information Systems and location models to planning of wastewater systems. Water Science & Technology **52**(3):1–8

Liu, S., Butler, D., Memon, F.A., Makropoulos, C., Avery, L., Jefferson, B. (2010). “Impacts of residence time during storage on potential of water saving for grey water recycling system.” Water Research **44**: 267-277.

Males, R. M. (1990). “History of Geographic Information Systems, with applications in water resources planning and management”. Optimizing the Resources for Water Management - Proceedings of the ASCE 17th Annual National Conference. 100-105.

Marsalek, J., Schaefer, K., Exall, K., Brannen L., and Aidun, B.(2002). Water Reuse and Recycling. Canadian Council of Ministers of the Environment, Winnipeg, Manitoba. CCME Linking Water Science to Policy Workshop Series. **3**.

Meadows D**. (**1996). Meadow Lake marks fourth year of zero liquid effluent pulping. Tappi Journal **79(1):** 63–68.

Metro Vancouver (2007). Wastewater. The greater Vancouver Sewerage and Drainage District Quality Control Annual Report 2007.

Metro Vancouver (2007) (1). Water Consumption Statistics Report. Operations and Maintenance Department.

Metro Vancouver (2008). GVWD and Municipal Water Demand by Sector. Policy and Planning Department.

Metro Vancouver (2009). "Liquid Waste Regulatory Program". Access electronically at http://www.metrovancouver.org/services/wastewater/treatment/Pages/treatmentplants.aspx on September 22, 2009.

Metro Vancouver (2010). "Liquid Waste Regulatory Program". Access electronically at http://public.metrovancouver.org/services/permits/Pages/sewerage.aspx on February 22, 2010

Metro Vancouver, (2010(1)). "Drinking Water on Tap. Progress Report for the Drinking Water Management Plan for the GVWD and Member Municipalities."

Mills, R.A. and Asano, T. (1996) "A retrospective assessment of water reclamation projects." Water Science and Technology. **33**(10–11):59–70

Natural Resources Canada (2006). "Better Water Use Means Better Savings." Accessed electronically at http://oee.nrcan.gc.ca/residential/personal/new-homes/water-conservation.cfm?attr=4 on June 9, 2010.

Natural Resources Canada (2009). "Population Density, 2001". Accessed electronically at http://atlas.nrcan.gc.ca/auth/english/maps/peopleandsociety/population/population2001/density2001/1. on July 29th, 2010.

O'Connor, G. A., Elliott, H. A., Bastian, R. K. (2008). "Degraded Water Reuse: An Overview." Journal of Environmental Quality **37**: 157–168.

Pearse, P. and Bocking, R (2002). "Putting a Value on Water: Is Full-Cost Pricing the Answer? Water and the Future of Life on Earth." Accessed electronically at http://www.sfu.ca/cstudies/science/water/pdf/Water-Ch15.pdf. on June 30, 2010.

Ratnapriya, E. and De Silva, R.P. (2009) "Location Opimization of Wastewater Treatment Plants Using GIS: A case study in Upper Maha Weli Catchment, Sri Lanka." Applied Geoinformatics for Society and Environment.

Revelle,C. and McGarity, A.E. (1997) Design and Operation of Civil and Environmental Engineering Systems Wiley-Interscience, New York, New York

Roeleveld P.J. and Maaskant, W. (1999). "A Feasibility Study on Ultrafiltration of Industrial Effluents." Water Science and Technology **39**(5): 73-80.

Schoenen, D. (2002). “Role of disinfection in suppressing the spread of pathogens with drinking water: possibilities and limitations.” Water Research **36:** 3874–3888

Selby, K.A., Puckorius P.R. and Helm K.R. (1996). “The use of reclaimed water in electric power stations and other industrial facilities”. Water, Air and Soil Pollution. **90**:183–193.

Shiklomanov, I.A. (1997). Comprehensive assessment of the freshwater resources of the world: Assessment of water resources and water availability in the world. World Meteorological Organization and Stockholm Environment Inst., Stockholm, Sweden.

Schultz Communications (1999). A Water Conservation Guide for Commercial, Institutional and Industrial Users. Report Prepared for the New Mexico Office of the State Engineer.

Stano, J. (2008). “Finding Common Ground: Using Water and Heat Optimization to Facilitate Eco-Industrial Development.” The University of British Columbia, Civil Engineering. **M.A.Sc Thesis**

Stantec Consulting (2010). “Core Area Wastewater Treatment Program Effluent Reuse and Heat Recovery for the University of Victoria and Surrounding Area”. Report for the Capital Regional District.

Steinberg, D.I. (1974) “Computational Matrix Algebra”. McGraw-Hill. New York, New York.

US Department Of Energy (2001). “Residential Energy Consumption Survey 2001”. Accessed electronically at http://www.eia.doe.gov/emeu/recs/recs2001/detailcetbls.html#heating on April 22, 2010.

US Environmental Protection Agency (2004). Guidelines for Water Reuse. Washington DC, Office of Water.

Vancouver Fraser Port Authority (2008). “Land Use Plan” Accessed electronically at http://www.portmetrovancouver.com/Libraries/PROJECTS/2008_VFPA_Land_Use_Plan.sflb.ashx on October 1st, 2010

Viessman and Hammer (2005) Water Supply and Pollution Control. Pearson Prentice Hall, New York.

World Health Organization. (WHO). (2004). *Water, sanitation and hygiene links to health. Facts and figures.* Retrieved from http://www.who.int/water_sanitation_health/publications/facts2004/en/index.html on July 15th, 2009.

World Water Council. (2006). Best Practices: Saving Water and Money. Retrieved from http://www.worldwatercouncil.org/index.php?id=25 on November 15th, 2009

Wong, D (2010). Email correspondence on October 20, 2010. R. Thoren. Vancouver.

Zhao Y.W, Qin, Y., Chen, B., Zhao, X., Li Y., Yin, X.A., Chen, G.Q. (2009) “GIS-based optimization for the locations of sewage treatment plants and sewage outfalls – A case study of Nansha District in Guangzhou City, China”. Communications in Nonlinear Science and Numerical Simulation **14:** 1746–1757

Appendix A – Python Code for Scenario 1 and 2

Python codes used to transfer and format data from ArcGIS are presented in Appendix A. These codes can be used for the first and second scenarios and deal with direct cascading of water between 102 industries (scenario 1) and then between 102 industries and a satellite WRF (scenario 2).

This first code, entitled "Print Array - 102", communicates directly with the databases in ArcMAP and determines the following:

- maximum inlet fractions between companies;
- maximum overall inlet fractions for each company;
- maximum outlet fractions between companies;
- maximum overall outlet fractions for each company;
- energy multipliers from the pumphouse to each company (kWh/m^3);
- energy multipliers between each company (kWh/m^3);
- inlet water volume requirements for each company; and
- outlet water volume generated for each company.

This information allows the exchange of water to be simulated, forms the constraints for the optimization, and is stored in independent arrays, which are printed as independent text files;

- Print outs of the arrays created in "PRINT ARRAY"; and
- A python script titled "PRINT MATLAB". This script formats all of the outputs from PRINT ARRAY for use in the Linprog function (linear programming solver) in Matlab.

PRINT ARRAY - 102

```
import sys, string, os, win32com.client, pythoncom, math, numpy, scipy
from scipy import *
from scipy.io import write_array
##########################################################################
####This Section accesses the GIS database, defines the workspace, calls the toolbox
####from ArcGIS and reads in the GIS database file.
pgp = win32com.client.Dispatch("esriGeoprocessing.GpDispatch.1")
pgp.Workspace = "C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc"
pgp.AddToolbox("C:\\Program Files\\ArcGIS\\ArcToolbox\\Toolboxes\\Data Management Tools.tbx")
COMPANY__dbf = "C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\No_Satellite\\Permit_Attribute_Cascade.dbf"
##############################################################################
####Make a list which contains all the GIS info for the companies.
####Count and store the number of companies in the variable called "Count"
Count = pgp.GetCount(COMPANY__dbf)
####Create a search through the database.
```

```
rows = pgp.SearchCursor(COMPANY__dbf)
####Initialize the search.
row = rows.Next()
####Create a list that can be populated with the company information.
company_array = {}
####Populate the list with industry information.
while row:
   OID = row.getvalue("OID")
   company_array[OID] = [row.getvalue("Name"),
row.getvalue("Qin"),row.getvalue("BODin"),row.getvalue("TSSin"),row.getvalue("Qout"),row.getvalue("
BODout"),row.getvalue("TSSout"),row.getvalue("Elev"),row.getvalue("OID")]
   row = rows.Next()

####Assign a number to correspond with each piece of data and the column that it is in
####the list
NAMEID = 0
h2oin = 1
BODin = 2
TSSIn = 3
h20out = 4
BODout = 5
TSSOut = 6
Elev = 7
OID = 8

#### Make a list that has the info for companies. #########
COMPANYinfo = {}
matchname = company_array.keys()
for name in matchname:
   column = 0
   COMPANYinfo[name] = [company_array[name][0], company_array[name][1],
company_array[name][2],company_array[name][3],
company_array[name][4],company_array[name][5],company_array[name][6],company_array[name][7],
company_array[name][8]]
Number_of_Companies = Count

######################################################################################
####Make a list that contains the distances between companies
DistanceInd__dbf = "C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\dist_ind.dbf"
w, h = Number_of_Companies, Number_of_Companies
inddistancearray = [[0]*w for i in range(h)]
row2s = pgp.SearchCursor(DistanceInd__dbf)
row2 = row2s.Next()
while row2:
   distrow = row2.getvalue("OriginID")-1
   distcolumn = row2.getvalue("Destinatio") - 1
   inddistancearray[distrow][distcolumn] = row2.getvalue("Total_Leng")
   row2=row2s.Next()
```

```
##############################################################################

##Make a list of the elevations of each company (elevation_array)

elevation_array = {}
matchname = COMPANYinfo.keys()
row = 0
for name in matchname:
   elevation_array[row] = COMPANYinfo[name][Elev]
   row += 1


####Make a list that contains all the Pumping kWh/m3 between companies(energylist)
w, h = Number_of_Companies, Number_of_Companies
energylist = [[None]*w for i in range(h)]
row = 0
matchname = COMPANYinfo.keys()
for name in matchname:
   column = 0
   while column < Number_of_Companies:
      energylist[column][row] = 0.00146 * inddistancearray[row][column] +
0.00419*(elevation_array[row] - elevation_array[column])
      column += 1
   row += 1
#print energylist
#### Also, this multiplier is based on a 6" pipe or 150 mm and provides energy in units
#### of kWh

####Convert the list into an array
Intercompany_transfer_energy_multiplier = numpy.array(energylist)

########################################################################
####Make a list that contains all the Initial Inlet Pumping kWh/m3 for
####companies(Inletenergylist - it is one column).

## For Vancouver THIS NEEDS TO BE ZERO! I left the other five rows in to show how the
## the calculation would be performed if the potable water source was not elevated.

w, h = Number_of_Companies, 1
Inletenergylist = [[0]*w for i in range(h)]
##column = 0
##row = 0
##while row < Number_of_Companies:
##    Inletenergylist[0][row] = 0.00000001*distancearray[0][row] + 0.000419*elevation_array[row]
##    row += 1
Inlet_energy_multiplier = numpy.array(Inletenergylist)

########################################################################
```

```
##From Metro Vancouver and BChydro, this is an average of the columbia and harbour pump stations
OutletEnergyMultiplier = 0.08

############################################################################
####Make a list that contains all the Initial Inlet Total Pumping Energy for
####companies(InletTotalEnergy). In the case of Vancouver, these values are zero.
InletTotalEnergy = {}
row = 0
while row < 1:
   column = 0
   matchname = COMPANYinfo.keys()
   for name in matchname:
      InletTotalEnergy[row, column] = COMPANYinfo[name][h2oin] * Inletenergylist[0][column] * 0
   row += 1

##########################################################################
##Make a list that contains all the Initial Outlet Pumping Total Energy for companies(OutletTotalEnergy)
OutletTotalEnergy = {}
row = 0
column = 0
matchname = COMPANYinfo.keys()
for name in matchname:
   OutletTotalEnergy[row,column] = COMPANYinfo[name][h20out] * OutletEnergyMultiplier
   column += 1

############################################################################
##########################################################################################
#############
##Make a list that contains all the Initial Pumping Eenrgy for each companies(InitialEnergy).
## The inlet energy is not included in this calculation because Vancouver's water source is elevated
## and does not require any pumping.
InitialEnergy = {}
column = 0
row = 0
while column < Number_of_Companies:
   InitialEnergy[column] = OutletTotalEnergy[row, column] #+ InletTotalEnergy[row, column]
   column += 1

############################################################################
####Calculate the Total Initial Pumping Energy for all companies(Total_inital_energy)
row = 0
column = 0
Total_inital_energy = 0
while column < Number_of_Companies:
   Total_inital_energy += InitialEnergy[column]
   column += 1

##Make a list that contains the distances from each industry to Iona. Then calculate the total amount
```

```
##of energy needed to pump the effluent of all companies there and make it that last entry in B.
DistanceWWTP__dbf = "C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\Ind_to_WWTP.dbf"
w, h = Number_of_Companies,1
indWWTPdistancelist = [[0]*w for i in range(h)]
row2s = pgp.SearchCursor(DistanceWWTP__dbf)
row2 = row2s.Next()
while row2:
   distcolumn = row2.getvalue("OriginID")-1
   indWWTPdistancelist[0][distcolumn] = row2.getvalue("Total_Leng")
   row2=row2s.Next()

####Make a list that contains all the Pumping kWh/m3 between companies and Iona(OUTenergylist)
w, h = Number_of_Companies, 1
OUTenergylist = [[None]*w for i in range(h)]
row = 0
column = 0
while column < Number_of_Companies:
   OUTenergylist[0][column] = 0.0000048 * indWWTPdistancelist[0][column] + 0.00419*(3 -
elevation_array[column])
   if OUTenergylist[0][column] < 0:
      OUTenergylist[0][column] = 0
   column += 1
OutletInitialEnergy = numpy.array(OUTenergylist)

##########################################################################
####This is a list that contains all of the outlet pumping requirements for each company

OutletInitialEnergy1 = {}
row = 0
column = 0
while column < Number_of_Companies:
   matchname = COMPANYinfo.keys()
   for name in matchname:
      OutletInitialEnergy1[row, column] = COMPANYinfo[column][h20out] * OUTenergylist[0][column]
   column += 1

###Now add up all of OutletInitialEnergy
row = 0
column = 0
Total_OUT_energy = 0
while column < Number_of_Companies:
   Total_OUT_energy += OutletInitialEnergy1[0,column]
   column += 1

##########################################################################
####make an array - QOUTBIG that has all the outlet water volumes. (i.e, number of
####companies X number of companies) (each row contains the outlet water volume,
```

```
####number of companies times)
#### Also, make another array (QOUTSMALL)that is a 1 X number of companies array
#### that holds the outlet water amount in a smaller list.
row = 0
w, h = Number_of_Companies, Number_of_Companies
QOUTBIGs = [[None]*w for i in range(h)]
while row < Number_of_Companies:
   column = 0
   matchname = COMPANYinfo.keys()
   for name in matchname:
      QOUTBIGs[column][row] = COMPANYinfo[name][h20out]
      column += 1
   row += 1
w, h = 1, Number_of_Companies
QOUTSMALLs = [[None]*w for i in range(h)]
column = 0
matchname = COMPANYinfo.keys()
for name in matchname:
   QOUTSMALLs[column][0] = COMPANYinfo[name][h20out]
   column += 1
QOUTBIG = numpy.array(QOUTBIGs)
QOUTSMALL = numpy.array(QOUTSMALLs)

##############################################################################
#### make an array - QINBIG that has all the inlet water volumes. (i.e, number of
#### companies X number of companies). (Each row contains the inlet water volume,
#### number of companies times)
#### Also, make another array (QINSMALL) that is a 1 X number_of_companies array
#### that holds the inlet water amount in a smaller list
row = 0
w, h = Number_of_Companies, Number_of_Companies
QINBIGs = [[None]*w for i in range(h)]
while row < Number_of_Companies:
   column = 0
   matchname = COMPANYinfo.keys()
   for name in matchname:
      QINBIGs[column][row] = COMPANYinfo[name][h2oin]
      column += 1
   row += 1
w, h = 1, Number_of_Companies
QINSMALLs = [[None]*w for i in range(h)]
column = 0
matchname = COMPANYinfo.keys()
for name in matchname:
   QINSMALLs[column][0] = COMPANYinfo[name][h2oin]
   column += 1
QINBIG = numpy.array(QINBIGs)
QINSMALL = numpy.array(QINSMALLs)
```

```
#### Assume there are n companies. Make an nXn list with each row and column
####representing a company where the rows include the amount available to take in BY
####the column company(matcharray).
#### matcharray will be used to determine the maximum fraction of companies output
#### that can be used by other companies.
#### Make another nXn list that contains rows which include the amount available to be
#### given TO the row BY the column(matchINarray)
#### matchINarray will be used to determine the maximum fraction of a company's input
####that can be substituted by other companies output.
#### i.e matchINarray will provide the upper bound in the optimization. matcharray will
#### be used as a constraint on the outlet fraction available for use by other companies.
NAMEID = 0
h2oin = 1
BODin = 2
TSSIn = 3
h20out = 4
BODout = 5
TSSOut = 6
#### Initialize the match arrays so they can be populated
matcharray = {}
matchINarray = {}
row = 0
matchname = COMPANYinfo.keys()
for name in matchname:
    column = 0
    matchname2 = COMPANYinfo.keys()
    for name2 in matchname2:
        if COMPANYinfo[name][BODout] <= COMPANYinfo[name2][BODin]:
            if COMPANYinfo[name][TSSOut] <= COMPANYinfo[name2][TSSIn]:
                matcharray[row, column] = COMPANYinfo[name2][h2oin]
                matchINarray[column, row] = COMPANYinfo[name][h20out]
            else:
                matcharray[row, column] = 0
                matchINarray[column, row] = 0
        else:
            matcharray[row, column] = 0
            matchINarray[column, row] = 0
        column += 1
    row += 1

############################################################################
####Maximum Fractions that can be Shared##############################
#### Make a list that contains all the outlet fractions(out_frac_array) and a list that
####contains inlet fractions(in_frac_array). These are the maximum sharing constraints
#### between individual industries (i.e. nXn).
#### Build another array that stores the maximum inlet (max_in_fractions_array) and
#### outlet fraction (max_out_fractions_array) that is available to share. These are the
```

```
#### overall inlet and outlet Constraints (i.e., nX1).
#### initialize the 4 arrays

w, h = Number_of_Companies, Number_of_Companies
in_frac_array = [[None]*w for i in range(h)]
w, h = Number_of_Companies, Number_of_Companies
out_frac_array = [[None]*w for i in range(h)]
w, h = Number_of_Companies, 1
max_in_fractions_array = [[None]*w for i in range(h)]
w, h = Number_of_Companies, 1
max_out_fractions_array = [[None]*w for i in range(h)]
w, h = Number_of_Companies, 1
TotalMaxin1 = [[None]*w for i in range(h)]
maxinfrac = 0
maxoutfrac = 1

##### GET THE OUT FRACTION
row = 0
matchname = COMPANYinfo.keys()
for name in matchname:
   column = 0
   outlet_frac = 0
   matchout = 0
   inlet_frac = 0
   matchin = 0
   while column < Number_of_Companies:
      matchout = matcharray[row, column]
      if float(matchout)/COMPANYinfo[name][h20out] >= 1.0000:
         out_frac_array[column][row] = 1.0000
         if row == column:
            out_frac_array[column][row] = 0
      else: out_frac_array[column][row] = float(matchout)/COMPANYinfo[name][h20out]

#### This next line keeps track of the total outlet fraction
      outlet_frac += matchout

#### GET THE IN FRACTION
      matchin = matchINarray[row, column]
      if float(matchin)/COMPANYinfo[name][h2oin] >= 1.0000:
         in_frac_array[row][column] = 1.0000
      else: in_frac_array[row][column] = float(matchin)/COMPANYinfo[name][h2oin]
      if [column] == [row]:
            in_frac_array[row][column] = 0
#### This next line keeps track of the total inlet fraction
      inlet_frac += matchin
      column += 1

###### This section of code constrains the total outlet and inlet fraction to be less than 1.
```

```
##
    newinlet = float(inlet_frac)
    newoutlet = float(outlet_frac)
    maxin = newinlet/COMPANYinfo[name][h2oin]
    maxout = newoutlet/COMPANYinfo[name][h20out]
    if maxout >= 1.0:
        max_out_fractions_array[0][row] = 1.0
    elif maxout < 0.0009:
        max_out_fractions_array[0][row] = 0.0
    else: max_out_fractions_array[0][row] = maxout

    if maxin >= 1.0:
        max_in_fractions_array[0][row] = 1.0
        TotalMaxin1[0][row] = maxin
    elif maxin < 0.0009:
        max_in_fractions_array[0][row] = 0.0
        TotalMaxin1[0][row] = 1
    else:
        max_in_fractions_array[0][row] = maxin
        TotalMaxin1[0][row] = maxin
    row += 1

####Convert all the lists to arrays
INfractions = numpy.array(in_frac_array)
OUTfractions = numpy.array(out_frac_array)
maxINfractions = numpy.array(max_in_fractions_array)
maxOUTfractions = numpy.array(max_out_fractions_array)


##########################################################################
#### Print all arrays to data files so that they can be evaluated prior to optimization
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\CompanyInfo.dat', COMPANYinfo)
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\QINBIG.dat',QINBIG.transpose())
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\QINSMALL.dat',QINSMALL.transpose())
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\QOUTBIG.dat',QOUTBIG.transpose())
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\QOUTSMALL.dat', QOUTSMALL.transpose())
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\OUTfractions_prop.dat', OUTfractions)
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\INfractions_prop.dat', INfractions)
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\maxINfractions.dat', maxINfractions)
```

```
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All Industries\\maxOUTfractions.dat', maxOUTfractions)
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All Industries\\TransferEnergy.dat', Intercompany_transfer_energy_multiplier)
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All Industries\\InletEnergy.dat',Inlet_energy_multiplier.transpose())
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All Industries\\OutletEnergy.dat',OutletInitialEnergy)
```

END PRINT ARRAY – 102

The next Python code, PRINT MATLAB – 102, formats the arrays made in PRINT ARRAY – 102 for input into MATLAB. The following are printed for use in MATLAB's 'linprog' function:

```
#### vector ub (upper bounds);
#### vector lb (lower bounds);
#### vector b (constraints);
#### vector (-)f (this contains all the inlet water requirements (objective scalers that are
#### multiplied by negative 1 as linprog finds the minimum of the function f*x); and
#### most of matrix A which gets multiplied by x such that A*x <=b – i.e., conditions that the
####constraints are applied to (maximum outlet fractions, maximum overall inlet
####fractions, maximum overall outlet fractions, and energy constraints).
##########################################################
```

PRINT MATLAB – 102

```
import sys, string, os, win32com.client, pythoncom, math, numpy, scipy, fpformat
from scipy import *
from scipy.io import write_array
from scipy.io import read_array
####Read in all the arrays that were printed with the last code
Number_of_Companies = 102
INfractions1 = read_array ('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\\All Industries\\Infractions_prop.dat')
QINBIG1 = read_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\QINBIG.dat')
QINSMALL1 = read_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\\All Industries\\QINSMALL.dat')
QOUTBIG1 = read_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\QOUTBIG.dat')
QOUTSMALL1 = read_array ('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\\All Industries\\QOUTSMALL.dat')
OUTfractions1 = read_array ('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\\All Industries\\OUTfractions_prop.dat')
maxINfractions1 = read_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\\All Industries\\maxINfractions.dat')
maxOUTfractions1 = read_array ('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\\All Industries\\maxOUTfractions.dat')
Intercompany_transfer_energy_multiplier = read_array ('C:\\Users\\Ryan\\Documents\\School
Work\\MASc Thesis\\Arc\\DataFiles\\All Industries\\TransferEnergy.dat')
Inlet_energy_multiplier1 = read_array ('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\\All Industries\\InletEnergy.dat')
OutletInitialEnergy = read_array ('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\\All Industries\\OutletEnergy.dat')
InletEnergy = numpy.ravel(Inlet_energy_multiplier1)
TransferEnergy = numpy.ravel(Intercompany_transfer_energy_multiplier)
OutletEnergy = numpy.ravel(OutletInitialEnergy)
##########################################################################
```

```
####Optional but can specify a required %energy reduction in the new scenario
PercentReduce = 0
#From Metro Vancouver and BChydro, this is an average of the columbia and harbour pump stations
OutletEnergyMultiplier = 0.08
##########################################################################
#### Reshape the arrays that were read in
##InitialGuessarray = numpy.reshape(InitialGuessarray1, (Number_of_Companies,
Number_of_Companies))
QOUTBIG2 = numpy.reshape(QOUTBIG1, (Number_of_Companies, Number_of_Companies))
QINBIG2 = numpy.reshape(QINBIG1, (Number_of_Companies, Number_of_Companies))
QINBIG = numpy.array(QINBIG2)

INfractions3 = numpy.reshape(INfractions1, (Number_of_Companies, Number_of_Companies))
row = 0
h, w = Number_of_Companies, Number_of_Companies
Infractions = [[0.0]*w for i in range(h)]
while row < Number_of_Companies:
  column = 0
  while column < Number_of_Companies:
    Infractions[row][column] = INfractions3[row][column]
    column += 1
  row += 1
INfractions = numpy.array(Infractions)
Yoriginal2 = numpy.copy(INfractions)
Yoriginal = numpy.ravel(Yoriginal2)

OUTfractions3 = numpy.reshape(OUTfractions1, (Number_of_Companies,Number_of_Companies))
row = 0
h, w = Number_of_Companies, Number_of_Companies
Outfractions = [[0.0]*w for i in range(h)]
while row < Number_of_Companies:
  column = 0
  while column < Number_of_Companies:
    Outfractions[row][column] = OUTfractions3[row][column]
    column += 1
  row += 1
OUTfractions = numpy.array(Outfractions)
outfracs2 = numpy.copy(OUTfractions)
outfracs = numpy.ravel(outfracs2)

row = 0
h, w = Number_of_Companies, Number_of_Companies
QOUTBIGS = [[None]*w for i in range(h)]
while row < Number_of_Companies:
  column = 0
  while column < Number_of_Companies:
    QOUTBIGS[column][row] = QOUTBIG2[row][column]
    column += 1
```

```
    row += 1
QOUTBIG = numpy.array(QOUTBIGS)
QOUTBIGRavelled = numpy.ravel(QOUTBIG)
Qin_QOUT_Ratio1 = QINBIG / QOUTBIG
QIN_QOUT_Ratio = numpy.ravel(Qin_QOUT_Ratio1)
QINBIGCOPY = QINBIG
QINBIGCONSTRAINT = numpy.ravel(QINBIGCOPY)

###################################################
##ADDED as QINBIG needs to be flipped
h, w = Number_of_Companies, Number_of_Companies
QINBIGFLIP = [[None]*w for i in range(h)]
row = 0
while row < Number_of_Companies:
    column = 0
    while column < Number_of_Companies:
        QINBIGFLIP[column][row] = QINBIG[row][column]
        column += 1
    row += 1
QINBIGFLIP1 = numpy.array(QINBIGFLIP)
QINBIGCONSTRAINT2 = numpy.ravel(QINBIGFLIP)

###############################################
### added because Qin_QOUT_RatioFLIP contains all the Ij / Ok
h, w = Number_of_Companies, Number_of_Companies
QOUTBIGFLIP = [[None]*w for i in range(h)]
row = 0
while row < Number_of_Companies:
    column = 0
    while column < Number_of_Companies:
        QOUTBIGFLIP[column][row] = QOUTBIG[row][column]
        column += 1
    row += 1
QOUTBIGFLIP1 = numpy.array(QOUTBIGFLIP)
Qin_QOUT_RatioFLIPPER = QINBIGFLIP1 / QOUTBIG2
Qin_QOUT_RatioFLIP = numpy.ravel(Qin_QOUT_RatioFLIPPER)

h, w = Number_of_Companies, Number_of_Companies
Qin_QOUT_RatioFLIPPER2 = [[None]*w for i in range(h)]
row = 0
while row < Number_of_Companies:
    column = 0
    while column < Number_of_Companies:
        Qin_QOUT_RatioFLIPPER2[column][row] = Qin_QOUT_RatioFLIPPER[row][column]
        column += 1
    row += 1
Qin_QOUT_RatioFLIPPER3 = numpy.ravel(Qin_QOUT_RatioFLIPPER2)
#####################################
```

```
###### NOW WE NEED TO CONVERT EVERYTHING TO Matlab format
##########################################################################
NumberYcons = Number_of_Companies * Number_of_Companies
NumberXcons = Number_of_Companies * Number_of_Companies
NumberTotalYcons = Number_of_Companies
NumberTotalXcons = Number_of_Companies
NumberYnonneg = Number_of_Companies*Number_of_Companies
constraints_length = NumberYcons + NumberXcons + NumberTotalYcons + NumberTotalXcons + 1 +
NumberYnonneg
number = 0
########################################################################
##################################
## first print out the objective scalers (i.e. - QINBIG)
matf = 0
f = "f = [-" + str(QINBIGCONSTRAINT2[matf]) + "; "
while matf < NumberYcons - 2:
   matf += 1
   f += "-" + str(QINBIGCONSTRAINT2[matf]) + "; "
matf += 1
f += "-" + str(QINBIGCONSTRAINT2[matf]) + "]"
print f

########################################################################
#### Now print the lower and upper bounds
#### Lower bound = 0
print "lb = zeros(" + str(NumberYcons) + ",1);"

##make the upper bound, which is the inlet fractions from the last code which has been named Yoriginal
in this code

matub = 0
ub = "ub = [" + str(Yoriginal[matub]) + "; "
while matub < NumberYcons - 2:
   matub += 1
   ub += str(Yoriginal[matub]) + "; "
matub += 1
ub += str(Yoriginal[matub]) + "]"
print ub

#############################################################
#####NOW MAKE THE 'A' Matrix
## The A matrix is not printed out in Python because it is too large and froze my computer
## Instead, the 4 parts of the A matrix are saved to file and called in MATLAB. See the
##following MATLAB code for exactly how this is done.
######First - add the x constraints - i.e., the ratio of in to out (xj,k = yj,k *(Ij / Ok)
######(EQUATION 11) -  Qin_QOUT_RatioFLIP contains all the Ij / Ok
##This part of the matrix is a sparse matrix with the values of Qin_QOUT_RatioFLIP as the
## diagonal. Instead of making it in python, Qin_QOUT_RatioFLIP is called from matlab where
```

```
##is it much easier and less memory demaning to create. This part of the matrix is 10404 x 10404

###### Second - add the summed y constraints - i.e., a list that is 102* 10404 units long to represent a
### 102 by 10404 matrix (EQUATION 8).
A2a = [0] * NumberYcons * Number_of_Companies
counter = 0
counter2 = 0
while counter2 <= NumberYcons - 1:
   counter3 = 0
   while counter3 < Number_of_Companies:
      A2a[counter * NumberYcons + counter2] = 1
      counter2 += 1
      counter3 += 1
   counter += 1
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\A_Matrix2.dat',A2a)

######third - add the summed x constraints - i.e., a list that is 102* 10404 units long to
######(EQUATION 10)
######represent a 102 by 10404 matrix
A3a = [0] * NumberYcons * Number_of_Companies
counter = 0
counter2 = 0
while counter2 < NumberYcons:
   counter3 = 0
   while counter3 < Number_of_Companies:
      A3a[counter * NumberYcons + counter3 * Number_of_Companies + counter] =
Qin_QOUT_RatioFLIPPER3 [counter * Number_of_Companies + counter3]
      counter2 += 1
      counter3 += 1
   counter += 1
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\A_Matrix3.dat',A3a)

##########################################################################
##FOURTH - add the energy constraint coefficients - i.e., a list that is 1 x 10404 units
## long to represent a 1 by 10404 matrix. This is the difference between the transfer
##energy and the energy required to get the water from the pumphouse and dispose of it.
##Left Hand Side of EQUATION 14
InitialEnergy = 0.0
counter = 0
while counter < Number_of_Companies:
   InitialEnergy += QOUTBIG[counter][0] * InletEnergy[counter] / 0.8
   counter += 1
A4a = [0] * NumberYcons
counter = 0
counter2 = 0
counter3 = 0
```

```
while counter2 < NumberYcons:
   A4a[counter2] = QINBIGCONSTRAINT2[counter2] * TransferEnergy[counter2] - (OutletEnergy[counter]
* QOUTBIGRavelled[counter2]) #- ((InletEnergy[counter] - .8 * OutletEnergyMultiplier ) *
QOUTBIGRavelled[counter2] / 0.8 )
   counter3 += 1
   counter2 += 1
   if counter3 == Number_of_Companies:
      counter += 1
      counter3 = 0
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\DataFiles\\All
Industries\\A_Matrix4.dat',A4a)
##############################################################################
######## NOW MAKE THE b vector. = 0
while count < Number_of_Companies - 1:
   b += str(sumOUTfracs[count]) + "; "
   count += 1
b += str(sumOUTfracs[count]) + "; "
###############################
counter = 0
sumINfracs = numpy.ravel(maxINfractions1)
sumOUTfracs = numpy.ravel(maxOUTfractions1)
b = "b = ["
count = 0
###### Add the constraint on each outlet fraction
while count < NumberYcons:
   b += str(outfracs[count]) + "; "
   count += 1
count = 0
###### Add the constraint on each inlet fraction
while count < Number_of_Companies:
   b += str(sumINfracs[count]) + "; "
   count += 1
count
counter2 = 0
FinalE1 = 0
FinalE2 = 0
while counter < Number_of_Companies:
   FinalE1 += ((InletEnergy[counter] - .8 * OutletEnergyMultiplier ) * QOUTBIG[counter][0] / 0.8 )
   FinalE2 += OutletEnergyMultiplier * QOUTBIG[counter][0]
   counter += 1
   counter2 += Number_of_Companies
b += str(273552) + "]"
## this was the amount of electricity used in the initial scenario as calculated in PRINT ARRAY - 102
print b
```

END OF PRINT MATLAB – 102

Appendix B – Python Code for Scenario 3

The following codes are applied to the third scenario. Here, exchanges between the satellite WRF and individual water users are explored. This code only deals with the mass balance and electrical constraints. The water quality constraints are not taken into account because it is assumed that reclaimed water from the satellite WRF is clean enough to be utilized for all purposes that use reclaimed water.
This script determines:

- Pumping requirements to get water from reservoir to water users
- Pumping requirements to move wastewater from water users to satellite WRF
- Pumping requirements to move reclaimed water from satellite WRF to companies
- Pumping requirements to move water from all water users to Iona WWTP

PRINT ARRAY – WATER USERS

```
import sys, string, os, win32com.client, pythoncom, math, numpy, scipy
from scipy import *
from scipy.io import write_array
##########################################################################
####This Section accesses the GIS database, defines the workspace, calls the tol##box
####from ArcGIS and reads in the GIS database file.
pgp = win32com.client.Dispatch("esriGeoprocessing.GpDispatch.1")
pgp.Workspace = "C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc"
pgp.AddToolbox("C:\\Program Files\\ArcGIS\\ArcToolbox\\Toolboxes\\Data Management Tools.tbx")
COMPANY__dbf = "C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\Powell\\New
Folder\\Final_Metered_Attributes.dbf"
##############################################################################
satellite_elevation = 8
####Make a list that contains all the GIS info for the companies.
####Count and store the number of companies in the variable called "Count"
Count = pgp.GetCount(COMPANY__dbf)
####Create a search through the database.
rows = pgp.SearchCursor(COMPANY__dbf)
####Initialize the search.
row = rows.Next()
####Create a list that can be populated with the company information.
company_array = {}
####Populate the list with industry information.
while row:
   OID = row.getvalue("OID")
   company_array[OID] = [row.getvalue("Name"), row.getvalue("Qin10"),
row.getvalue("BODin"),row.getvalue("TSSin"),row.getvalue("Qout"),row.getvalue("BODout"),row.getval
ue("TSSout"),row.getvalue("Elev")]
   row = rows.Next()
```

```
####Assign a number to correspond with each piece of data and the column that it is in
####the list
NAMEID = 0
h2oin = 1
BODin = 2
TSSIn = 3
h20out = 4
BODout = 5
TSSOut = 6
Elev = 7

#### Make a list that has the info for companies. #########
COMPANYinfo = {}
matchname = company_array.keys()
for name in matchname:
   column = 0
   COMPANYinfo[name] = [company_array[name][0], company_array[name][1],
company_array[name][2],company_array[name][3],
company_array[name][4],company_array[name][5],company_array[name][6],company_array[name][7]]
Number_of_Companies = Count

########################################################################
##Make a list of the elevations of each company (elevation_array)

elevation_array = {}
matchname = COMPANYinfo.keys()
row = 0
for name in matchname:
   elevation_array[row] = COMPANYinfo[name][Elev]
   row += 1

####Make a list that contains all the Initial Inlet Pumping kWh/m3 for
####companies(Inletenergylist - it is one column).
w, h = Number_of_Companies, 1
Inletenergylist = [[0]*w for i in range(h)]

####Convert the list into an array
Inlet_energy_multiplier = numpy.array(Inletenergylist)
##print Inlet_energy_multiplier

#########################################################################
####Make a list that contains all the Initial Inlet Total Pumping Energy for companies - InletTotalEnergy
#In the case of Vancouver, these values are all zero
InletTotalEnergy = {}
row = 0
while row < 1:
   column = 0
```

```
    matchname = COMPANYinfo.keys()
    for name in matchname:
        InletTotalEnergy[row, column] = COMPANYinfo[name][h2oin] * Inletenergylist[0][column]
        column += 1
    row += 1

##############################################################################
####for output energy, make a list that contains the distances between companies and the satellite
Cent_Ind_Dist__dbf = "C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\Powell\\New Folder\\Powell_ind_sat_dist.dbf"

w, h = (Number_of_Companies), 1
Cent_ind_distarray = [[0]*w for i in range(h)]
row3s = pgp.SearchCursor(Cent_Ind_Dist__dbf)
row3 = row3s.Next()
row = 0
while row3:
    rowsearch=0
    while rowsearch < Number_of_Companies:
        distcolumn= row3.getvalue("ObjectID") - 1
        Cent_ind_distarray [row][distcolumn] = row3.getvalue("Total_Leng")
        row3 = row3s.Next()
        rowsearch+=1
    row+=1

##############################################################################
#Make a list that contains all the Pumping kWh/m3 between the satellite and water meters
# for when the the treated water is being pumped back to the companies(OutletEnergylist)

w, h = Number_of_Companies, 1
OutletEnergylist = [[None]*w for i in range(h)]
row = 0
column = 0
while row < Number_of_Companies:
    OutletEnergylist[0][row] = 0.00146 * Cent_ind_distarray[0][row] + 0.00419*(satellite_elevation - elevation_array[row])
    row += 1
Centennial_company_energy_multiplier = numpy.array(OutletEnergylist)

###########################################################################################
## Make a list that contains the outlet pumping energy required to get effluent from the water metered
## properties to the satellite plant so you can put it in the A matrix.
## For Vancouver, don't worry about this section - ALL VALUES are < ZERO, even for Powell St WRF###
w, h = Number_of_Companies, 1
ToSatelliteEnergyList = [[None]*w for i in range(h)]
row = 0
column = 0
while row < Number_of_Companies:
```

```
  ToSatelliteEnergyList[0][row] = 0.0000048 * Cent_ind_distarray[0][row] + 0.00419*(satellite_elevation
- elevation_array[row])
  if ToSatelliteEnergyList[0][row] < 0:
    ToSatelliteEnergyList[0][row] = 0
  row += 1

##############################################################################################
########
## This is to calculate the amount of energy required to pump water from the water useres to
## Iona, ie., the initial electrical consumption. This value will be used as the last entry
## in the b vector in the MATLAT script
OutletEnergyMultiplier = 0.08
InitialOutletEnergy = {}
row = 0
while row < 1:
  column = 0
  matchname = COMPANYinfo.keys()
  for name in matchname:
    OutletTotalEnergy[row,column] = COMPANYinfo[name][h20out] * OutletEnergyMultiplier
    column += 1
  row += 1
print "InitialOutletEnergy = ", InitialOutletEnergy

#############################################################################
#### Also, make another array (QOUTSMALL)that is a 1 X number of companies array
#### that holds the outlet water amount in a list.
w,h = 1,Number_of_Companies
QOUTSMALLs = [[None]*w for i in range(h)]
column = 0
matchname = COMPANYinfo.keys()
for name in matchname:
  QOUTSMALLs[column][0] = COMPANYinfo[name][h20out]
  column += 1
QOUTSMALL = numpy.array(QOUTSMALLs)

#############################################################################
##make an array (QINSMALL) that is a 1 X number_of_companies array
#### that holds the inlet water amount in a list
w,h = 1,Number_of_Companies
QINSMALLs = [[None]*w for i in range(h)]
column = 0
matchname = COMPANYinfo.keys()
for name in matchname:
  QINSMALLs[column][0] = COMPANYinfo[name][h2oin]
  column += 1
QINSMALL = numpy.array(QINSMALLs)

###########################################################################
```

```
## Print all arrays to data files so that they can be evaluated prior to optimization
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\Metered_Powell\Metered_Powell10_CompanyInfo.dat', COMPANYinfo)
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\Metered_Powell\Metered_Powell10_QINSMALL.dat',QINSMALL.transpose())
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\Metered_Powell\Metered_Powell10_QOUTSMALL.dat',
QOUTSMALL.transpose())
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\Metered_Powell\Metered_Powell10_TransferEnergy.dat',
Centennial_company_energy_multiplier)
write_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\Metered_Powell\Metered_Powell10_ToSatelliteEnergyList.dat',
ToSatelliteEnergyList)
```

END OF PRINT ARRAY – WATER USERS

The next Python code, PRINT MATLAB – WATER USERS, prints values for

- Upper bounds – (All 1 in this case)
- Lower Bounds – (All 0 in this case)
- f vector – (water inlet requirements for all water users)
- A-Matrix (energy requirements for each company)
- b – vector (Cumulative electricity used to pump water from water users to Iona)

PRINT MATLAB – WATER USERS

```
import sys, string, os, win32com.client, pythoncom, math, numpy, scipy, fpformat
from scipy import *
from scipy.io import write_array
from scipy.io import read_array

####Read in all the arrays that were printed with the last code
QOUTSMALL1 = read_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\Metered_Cent\Metered_Cent10_QOUTSMALL.dat')
QINSMALL1 = read_array('C:\\Users\\Ryan\\Documents\\School Work\\MASc
Thesis\\Arc\\DataFiles\Metered_Cent\Metered_Cent10_QINSMALL.dat')
Centennial_company_energy_multiplier = read_array ('C:\\Users\\Ryan\\Documents\\School
Work\\MASc Thesis\\Arc\\DataFiles\Metered_Cent\Metered_Cent10_TransferEnergy.dat')

QINSMALL = numpy.array(QINSMALL1)
QOUTSMALL = numpy.array(QOUTSMALL1)
TransferEnergy = numpy.array(Centennial_company_energy_multiplier)

Number_of_Companies = 2283
#NumberYcons = Number_of_Companies * Number_of_Companies
OutletEnergyMultiplier = 0.08

###########################################################################
##print out the objective scalers (i.e. - QINBIG)
matf = 0
f = "f = [-" + str(QINSMALL[matf]) + "; "
while matf < Number_of_Companies - 2:
   matf += 1
   f += "-" + str(QINSMALL[matf]) + "; "
matf += 1
f += "-" + str(QINSMALL[matf]) + "]"
print f

###########################################################################
##print the upper and lower bounds
```

```
Lower bound = 0
print "lb = zeros(" + str(Number_of_Companies) + ",1);"

upper bounds = 1
print "ub = ones(" + str(Number_of_Companies) + ",1);"

#######################################################################
##This A matrix only applies to the electrical constraint. It takes the difference between the energy
##required to pump the recycled water from the WWTP back to the facilies and the energy required to
##get the potable water and dispose of it in the original scenerio.

A1 = [0] * Number_of_Companies
counter2 = 0
while counter2 < Number_of_Companies:
   A1[counter2] = QINSMALL[counter2] * TransferEnergy[counter2] - (OutletEnergyMultiplier *
QOUTSMALL[counter2])
   counter2 += 1

matA = 0
A = "A = [" + str(A1[matA]) + ", "
while matA < Number_of_Companies - 2:
   matA += 1
   A += str(A1[matA]) + ", "
matA += 1
A += str(A1[matA]) + "];"
print A

#########################################################################
##print up the b vector, which is the amount of electricity the companies currently use to pump their
effluent to Ionan Vancouver
b = str(687977.84)  + ";"

print b
```

END PRINT MATLAB - WATER USERS

Appendix C - MATLAB Code

Scenario 1 and 2

```
options = optimset('Display','Iter', 'MaxIter', 250);
A1a = load('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\ DataFiles\\All Industries\\A_Matrix1.dat');
A1S = sparse([1:10404],[1:10404],A1a,10404,10404);
A2a = load('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\ DataFiles\\All Industries\\A_Matrix2.dat');
A2b = reshape(A2a,10404,102)';
A3a = load('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\ DataFiles\\All Industries\\A_Matrix3.dat');
A3b = reshape(A3a,10404,102)';
A4a = load('C:\\Users\\Ryan\\Documents\\School Work\\MASc Thesis\\Arc\\ DataFiles\\All Industries\\A_Matrix4.dat');
A4b = reshape(A4a,10404,1)';
A = [A1S;A2b;A3b;A4b]
f = [copy and paste from python]
lb = [copy and paste from python]
lb = zeros(10404,1);
b = [copy and paste from python]
[x,fval,exitflag,output] = linprog(f,A,b,[],[],lb,ub,[],options);
X = reshape(x,102,102)';
xlswrite('testing.xlsx', X, 'results_aug', 'B2');
```

Note: The last line of the program writes the results to an Excel file.

Scenario 3

```
options = optimset('Display','Iter', 'MaxIter', 150);
A = [copy and paste from python]
f = [copy and paste from python]
lb = zeros(2283,1);
ub = ones(2283,1);
b = 687977.8;
[x,fval,exitflag,output] = linprog(f,A,b,[],[],lb,ub,[],options);
X = reshape(x,2283,1);
xlswrite('Centennial20_Water_user_results.xlsx', X, 'NewQin_Aug', 'B2');
```

Note: The last line of the program writes the results to an Excel file.