PLANNING AND IMPLEMENTATION OF SUSTAINABLE STORMWATER MANAGEMENT SYSTEMS IN THE CITY OF VANCOUVER: THE GREEN ROOF EXAMPLE

by

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Abstract

Imagine a city that utilizes the rain that falls on it as a resource instead of managing it as a waste. This city is planned, designed and engineered in ways that help to preserve and bolster the ecosystem within which it sits. The costs to the taxpayer are lower than other municipalities that have preserved the status quo of managing their stormwater. The city itself is less reliant on inputs of materials and energy from outside its borders. The people who live in this city are more cognizant of their natural environment, understand the meaning of developing sustainably and experience less of the "concrete jungle" than do people in other contemporary cities. The planners, designers, engineers and decision-makers use stormwater management as a tool to achieve a more sustainable city that is reflective of local ecological functions, as well as global materials and energy availability. In this thesis, the stormwater management contributions to achieving such a reality in Vancouver, British Columbia are investigated, while a framework for applying sustainable stormwater management systems to this and other contexts is constructed. Data and information are gathered through literature review, case study and interviews. The results of the study illustrate a more sustainable and integrated stormwater management framework and suggest that it is possible to incrementally shift the system towards this over time. The study also shows that it can be more ecologically and economically sustainable to do so. While there appear to be many opportunities for this shift to sustainable stormwater management systems, there are also significant, yet surmountable, institutional and epistemological barriers that must be addressed.

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Acknowledgements

There keep coming these moments in my life where I realize that planning is what I want to be doing, where I belong. I have never been one of those people who fall into their profession, their calling. My path to SCARP wound all over the place; Thailand, Ottawa, London, Hong Kong, Victoria, Whistler, the Boreal and rainforests of Canada, the desert and strip of Las Vegas, the Sea of Cortes in Baja Mexico. Really it wasn't until hitchhiking "through" Los Angeles that planning started calling my name. There were two lifts specifically that made me contemplate the role that people can play in shaping our built environment and thus strongly affecting the natural world. The first took place in San Bernardino County in southwestern California – a veritable wasteland of the human spirit imbued within the concrete ground under my feet and the glares of the frustrated inhabitants. The strip malls therein replaced the kids on bikes as the omnipresent component of my childhood urban reality. The second ride picked me up immediately after I walked across the San Andreas Fault. While crossing that tectonic seam in the earth, the only thing I could think about was the "clean start" I'd been imagining would take place for LA if the plates were to suddenly shift. Hoping for an earthquake was not the option that I wanted to pursue in making the shift to a better place for us all to live. I saw the rapid urbanization of North America and indeed the rest of the planet in the growing cities, the centres of potential change, the locus of human impact on the world. Somewhere along the way since those days, my friend Justin Cox provided the model strength of character, determination and integrity that I needed to trend successfully down this path. Along with my close family and very tight group of friends, I found the focus to pursue my career path. The early guidance from my supervisor, Dr. Bill Rees, the midpoint encouragement from my business partner Jon Frantz, the ongoing jeering from another Justin and the late prodding from a record-breaking PhD student got me through to the end. This end to my thesis, by the way, happily coincided with the introduction to the love of my life. The rest is still happening.

1.0 Introducing Stormwater Management in Vancouver

The overall purpose of this thesis is to determine how cities in general and Vancouver in particular can most effectively and sustainably address the issue of stormwater management. This thesis addresses the system requirements and features of sustainable stormwater management systems. As well, the opportunities and constraints to implementation are explored. The discussion is centred on physical infrastructure planning, but also considers the interrelated responsibilities of decision makers, planners, engineers and designers. To answer the research questions posed in this thesis, the results of interviews with relevant professionals and researchers are combined with a literature review and case studies of two other North American municipalities.

The reality of rainfall is inescapable; it is an amazing natural process indispensable to life on earth. Rain/snowfall is the ultimate source of freshwater here in southwestern BC, it "infiltrates every aspect of our biological, cultural and spiritual lives" (France 2000). However rainwater becomes an issue when it falls on a city's impermeable surfaces and turns into stormwater; a city generates and is the source of stormwater. Overland flowing stormwater is a 'problem'; a costly inconvenience at best and at worst, a potential threat to property and health of both humans and the natural environment. However urban stormwater runoff is much more than these things; it has become a very expensive issue in cities and is a major pollutant source and ecological contaminant. As a result, stormwater management is an integral component to the sustainability of cities.

Rainfall is a reality that we clearly experience here on the south west coast of Canada more than any other major urbanized region in the country. Of course rain also visits the rest of Canada's major cities, but it does so with less frequency than it does Vancouver. This city sits, after all, where a temperate rainforest once grew. What happens to all that water that falls on Vancouver each year? Where does it now go, how does it get there and how have the natural systems responded to the disruptions caused by urbanization? These questions have simple answers, yet they are answers that lead to the much more complex investigation that is the subject of this thesis.

Our world's cities are highly rational in their functioning, organization and built forms (Rifkin 1989; Sandercock 1998, Iyer-Raniga & Treloar 2000). They are composed of asphalt, steel and concrete; impermeable and impervious materials. Picture Vancouver's landscape: the area is covered by streets and sidewalks, roofs, vacant lots, parking lots, lawns and the occasional park[1]. Generally, city surfaces are resistant to rainwater infiltration and Vancouver's 113 km^2 are no exception. As a result, the 1,239.3 mm on average of rain that falls per year on Vancouver[2] (Environment Canada 2004) has to go somewhere now that the natural rivers, waterways, vegetation and overall hydrological regime are no longer intact. Stormwater management (SWM) systems must be built.

By means of technical engineering, stormwater in Vancouver today is collected, piped and transported off the city's surfaces in a highly efficient, linear, unidirectional fashion (ULI 1975; Condon & Isaac 2003). This water eventually ends up in either the Burrard Inlet, Fraser River, or Straight of Georgia. The methods of SWM are highly effective at removing water offsite, but because the system is designed for throughput of stormwater, both the huge associated costs to the taxpayer and to the receiving ecosystems are ignored. The linear design of the system means rainwater that falls on the city is transported off the land without making use of it ecologically, socially or monetarily.

There has been movement in the right direction in Vancouver. Projects such as the *Rain Barrel* program, *Sump Exfiltration* pilot project, the *Crown Street Sustainable Streetscapes and Fish Habitat Enhancement Demonstration Project*, an impermeability bylaw related to single family residential properties and the *Roof Leader Disconnection* pilot project (Pedersen 2000, City of Vancouver website 2005) have acknowledged the issue. These initiatives demonstrate that the stormwater issue is being taken seriously in some few areas of planning, design, engineering and decision-making. These programs are indeed a step in the right direction, a foundation that alone is not enough, but upon which we must now continue to build towards a more sustainable system.

[1] See table 2.0 for a breakdown of Vancouver's land uses.
[2] On average. Measurements taken at City Hall on Cambie St. at 12th Ave. Average rainfall taken at UBC is 1,226.5mm, while the average at Vancouver harbour is 1,479.9mm.

Humans have altered the landscape to build our cities, resulting in disruption to the natural systems' methods of dealing with rainwater. Replacing natural systems with scientifically engineered systems of our own has changed forever the natural functioning of the landscape and created a dependence on external inputs of materials and energy (Iyer-Raniga & Treloar 2000). Accompanying the hydrological changes (Boontilleke et al 2005) are myriad other negative effects including: polluted water bodies, loss of marine habitat and biodiversity, loss of soils' water-retention abilities and decreased groundwater recharge. These are but a few of the stormwater-related problems accompanying the increase in impermeable surfaces of our cities.

Conventional, linear throughput SWM systems convey water offsite rather than allowing infiltration into the ground. The altered landscapes of our cities do not change localized climatic patterns enough to dramatically limit the rain that falls on them[3], so we must therefore find some way of mimicking the drainage capabilities and capacities of the displaced natural systems. Countless ways of accomplishing this have been attempted, many of which have ended/are ending in failure, yet some loom on the horizon as potentially sustainable options.

The problems addressed in this thesis are experienced directly in a continuously degrading natural environment, high dollar costs, growing scarcity of materials and energy and an overall loss of ecological awareness in people. The root of the problem, however, lies buried deep within the origins of the path-dependent behaviour that we experience today. Though of noble original intent, our present day SWM systems are no longer appropriate. The mid 19th century saw cities fraught with sanitary problems, overcrowding, immense localized pollution, disease, mobility and access issues. SWM engineering heroically answered the call and alleviated many of these immediate urban problems by building extensive sewerage and drainage systems.

[3] The urban heat island effect has been shown to increase temperatures in and around large cities by a few degrees Celsius, accompanied by a corresponding increase in humidity. There is also an increase in airborne particulate that can act as both reflective material to outgoing infrared radiation, as well as catalytic particles for raindrop formation. Vancouver does not suffer from this problem as much as many other large cities.

Born out of the scientific revolution, the linear methods by which we engineered our cities for the last 150 years have allowed us to live much cleaner and orderly urban lives. Arguably though, the eventual long-term costs of the early systems will outweigh the benefits. This eventuality could hardly be known at the time. The associated negative aspects were not immediately felt and day to day quality of life was greatly improved, but as time has passed, the lag between the building of the systems and the impacts of their negative effects diminishes. The monetary and ecological costs catch up to us, begin to accumulate and leave us with the problem of how to change our entrenched planning behaviour, methods and tools to address them accordingly.

Our current methods of SWM are not sustainable. They are accompanied by numerous negative impacts including, but not limited to:

- increasing and ongoing costs in building, repair and maintenance of the system;
- disruption of the hydrological regime, i.e. groundwater recharge, streamflow;
- increased periods of peak stormwater flow and pollutant flushing off surfaces;
- increased total levels of stormwater flows, causing the need for larger sized infrastructure;
- higher levels of pollutant loading in waterways;
- loss of marine and terrestrial ecological integrity;
- loss of aesthetics and aesthetic potential;
- increased heavy construction and disruption to the use of public space;
- decreased environmental awareness in the public;
- further entrenchment along the unsustainable path of dependence.

(ULI 1975; Tjanllingii 1995; Arnold 1996; Dreisetl in Rowney et al 1997; Li et al 1998; Burton et al 2002; Coppes 2002; Dreisetl 2004).

Examination of these negative impacts shows us clearly what is unsustainable in our current SWM system. Recognizing this reality is essential if we are to design and build systems that take these potential issues into consideration and limit the possible negative effects. Discovering a sustainable system, the benchmark of which must be that short and long term benefits exceed its short and long term costs[4], is at the heart of this research.

[4] Chapter 4.0 provides the reader with a discussion on cost benefit analyses.

Why the focus on sustainability as a theoretical framework? The answers are simple:

A. The historical record[5] clearly details the collapse of countless unsustainable civilizations, a fate that, as a rational, educated and wise society, we would logically strive to learn from and avoid.

B. In April of 2002, the City of Vancouver officially adopted a series of principles and definitions of sustainability, by which future planning and decision-making would be guided. Of note in these principles are numbers 1, 2, 4, 5, 7, 10. In these principles lie the basis and rationale for a sustainable SWM system in this city and they are as follows:

Vancouver City Principles of Sustainability

1. Today's decisions must not compromise the choices of our children and future generations.
2. We are all accountable for our individual and collective actions.
3. Resources must be used fairly and efficiently without compromising the sustainability of one community for another.
4. Using renewable resources is encouraged and supported, while the use of non-renewable resources should be minimized.
5. Renewable resource consumption should not exceed the rate of regeneration.
6. Strong collaboration and open communications between the public, the business sector, and all levels of government is important.
7. We value cultural, economic, and environmental diversity.
8. A community should provide a safe, healthy, and viable setting for human interaction, education, employment, recreation, and cultural development.
9. A sustainable Vancouver contributes to, and provides leadership towards regional, provincial, national, and global sustainability.
10. The Vancouver economy should move forward from its dependence on non-renewable carbon-based fuels, particularly for transportation, which are likely to fluctuate in price and supply.

From the Vancouver City Website: http://vancouver.ca/sustainability/

The very notion of 'sustainability' implies a conceptual framework that assumes planning and actions are undertaken for both the short and long-term betterment of human beings. The phrase 'sustainable development' has become a catch-all, subjectively-defined label.

[5] See Joseph Tainter's The Collapse of Complex Societies, or Ronald Wright's A Short History of Progress, or Collapse by Jared Diamond.

Many arguments are made on the grounds of sustainability that are not well thought-out, not steeped in historical knowledge or systems' understanding, nor based on real data. Sustainability, simply, is the notion that we want our civilization to progress and develop far beyond our own generation's brief time on the planet. I offer here a concise, working definition for sustainable development, one that is based in the related literature and upon which I will expand in later chapters.

The definition presented here is based in the UN Declaration of Human Rights and Freedoms (1989). Sustainable development is dynamic and inclusive planning and actions for the betterment of all humanity that can be pursued only if these processes and outcomes are not at the expense of ecological, social, cultural, or human welfare. It must be possible for every person on the planet to engage in any and all human activities, structures and systems; if one person is allowed an action, all should be allowed that same. Per person shares of the Earth's natural capital must not be spent such that the spending reduces the possibilities for future generations' planning and actions for their own betterment. Sustainable development defines the parameters for the egalitarian distribution of the global aggregate of all human activities over time.

In the following chapters of this thesis, I address these three research objectives:

1. To develop system requirements and criteria for the most sustainable means of dealing with the rainwater that falls on urban centres in general and specifically in Vancouver, BC;
2. To discover the opportunities for and constraints to implementing such systems, specifically in the City of Vancouver;
3. To chart a course for addressing these options.

This thesis is a work of optimism, hope and opportunity for city-building and the movement to a sustainable world. The fundamental assumption herein is that though the path to the sustainable city is fraught with difficulty, successfully navigating it is possible. The urgency with which we move forward cannot be stated strongly enough.

2.0 The Problems of Managing Urban Stormwater

"Infrastructure - *the substance, or underlying foundation, especially the basic installations and facilities on which the continuance and growth of a community or state depends*".

Webster's New World Dictionary

The introduction of new land uses will inevitably change the permeability of the land's surface. When natural regimes are altered, the natural system of draining water off the land will be changed, resulting in some form of negative hydrological and/or ecological impacts (Schueler, 1987; Harbor 1994; Kolling, 1995; Li et al, 1998; Rowney et al, 1999). Even minor disturbances to soil and/or plant regimes will have an effect on the drainage characteristics of the land. The vegetation cover of an area performs many hydrological functions, including draining the land, regulating localized humidity and temperature, protecting from wind erosion, and providing soil stability for groundwater infiltration (IAHS 1977; Page 1987; Burton & Pitt 2002).

How much of a typical city is covered by impermeable surface? Cities are known as "concrete jungles" because they have given rise to what seems like a dangerous chaos covered, not in vines, trees and plants, but instead by inorganic, non-feeling, human-built, hard, impermeable/impervious materials. As the percentage distribution of land uses in **Table 1** shows, Vancouver is very much a typically impermeable city.

In a natural, undisturbed state, the ground is almost entirely pervious, with occasional impervious rock outcrops. In the natural system, rainwater falls to the ground and follows its naturally-developed and gravity-influenced course into the larger watershed. The water is taken up by plants and cools the site as it leaves through evapotranspiration or evaporation off surfaces and is finally taken up into receiving water bodies through channels, streams, rivers and as groundwater. In the natural system, there is almost no such thing as "stormwater", as this is the runoff phase of falling precipitation once it lands on impervious surfaces and begins to flow. Indeed cities are the very cause and source of stormwater.

Table 1. Percentage Land Use in Vancouver by Type

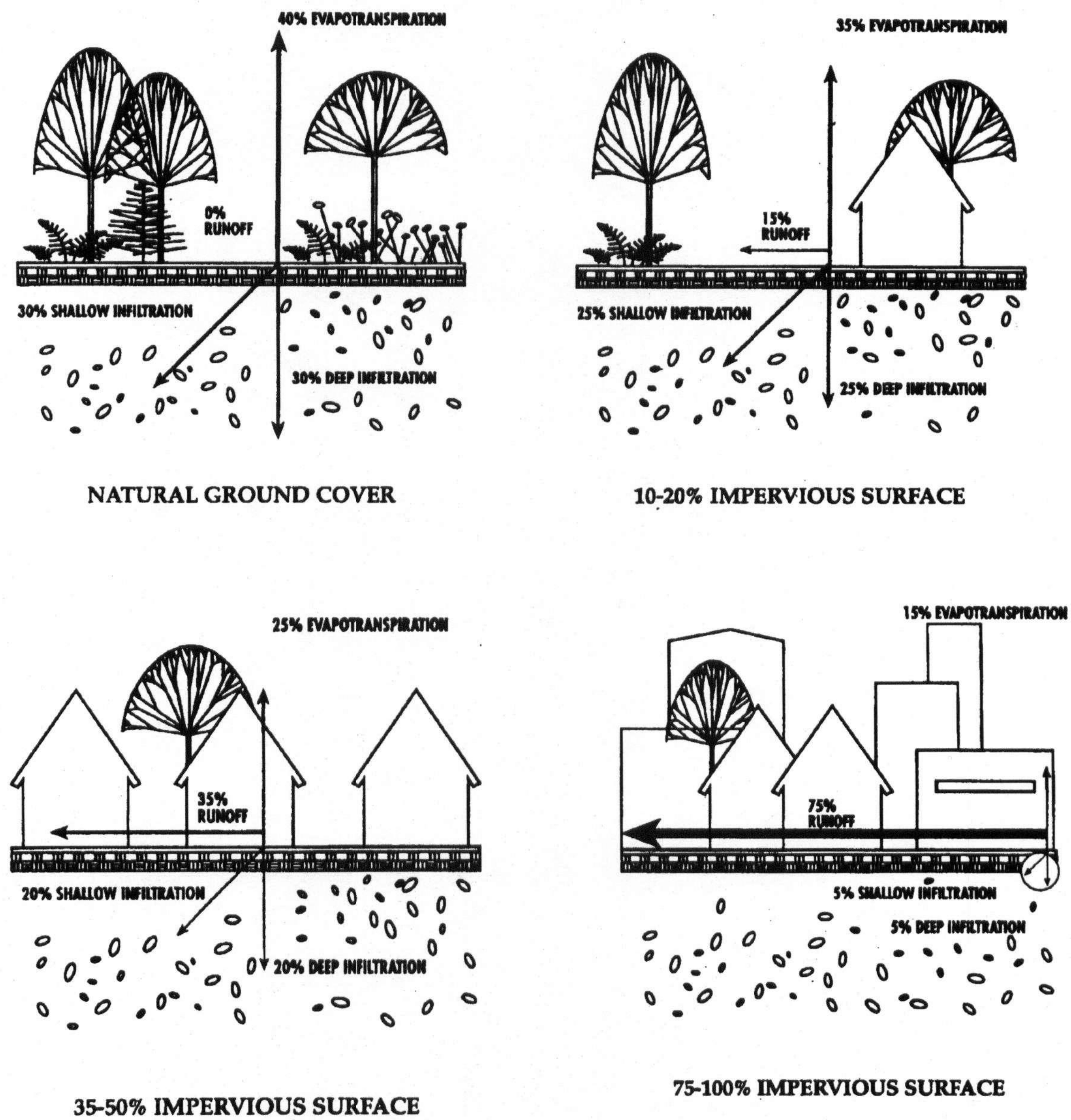
The contemporary physical manifestation of the land uses listed in ***Table 1*** facilitates the production of stormwater. As a landscape increases in impermeable surfaces it takes on new infiltration dynamics, many of which are irreversible changes to the regime.

Land Use Type	Percent	Area (km^2)
Single family (see pg. 21-22)	25	28.14
Single family + suite	7	7.91
Duplex, Rowhouse	2	2.16
Apartment	3	3.29
Apartment + Commercial	1	1.13
Commercial	4	4.41
Social or Public Service	2	2.0
School	2	2.26
Cultural or Recreational	2	2.25
Park or Other Open Space	10	10.8
Golf Course	2	2.16
Wholesale or Storage	2	2.06
Manufacturing	1	1.13
Transport, Communications, Utilities	3	3.29
Vacant or Under Construction	2	2.16
Streets, Lanes, Sidewalks	32	36.05
Total	**100**	**111.2**

Adapted from Pedersen, 2000 and Vancouver Facts Sheet 2004

The disturbances to the natural system caused by the built environment will be manifested in variable rates and quantities of runoff. The system may typically look like the depiction in **Figure 2**. Due to the increased area of impervious surface in urban settings, there is greatly decreased infiltration of precipitation into groundwater and an increase in surface runoff (**Figure 1**).

Figure 1. Hydrologic Changes Associated with Increased Impervious Surfaces



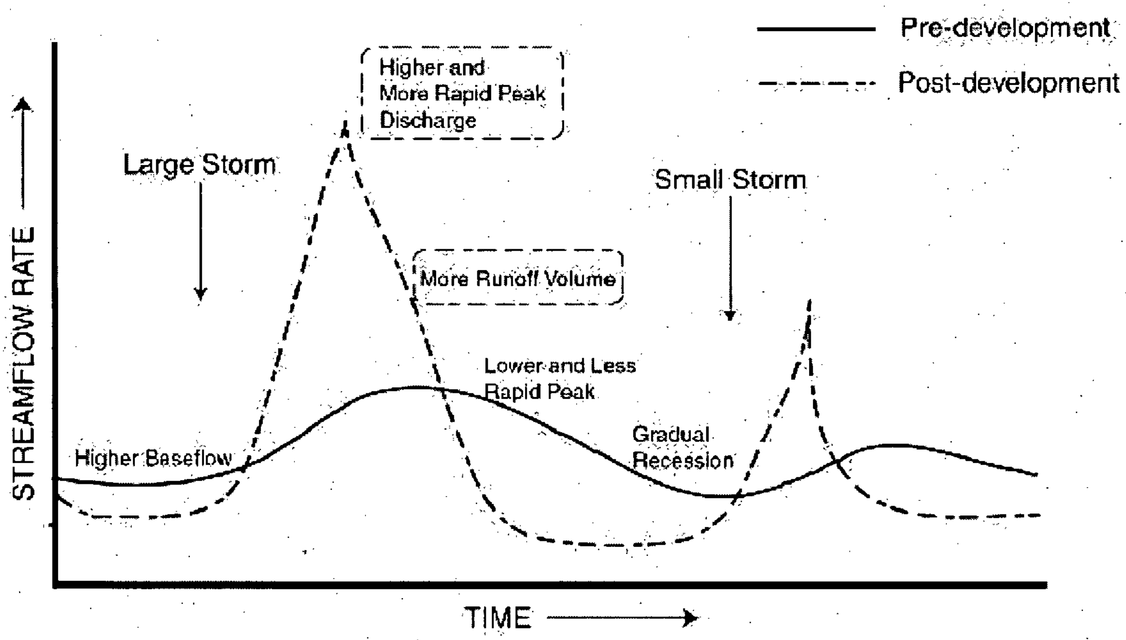
Adopted from *Meadows in the Sky* (Pedersen 2000).

Centralized stormwater facilities concentrate runoff from large surface areas and channel it into stream flow. In many cases this leads to several outflow pipes at specific locations where the water is released back into the system[6]. However this does not match the

[6] See the GVRD's Inventory of Stormwater Outfalls and Discharges (1999).

natural system's abilities to mitigate the energy that stormwater possesses[7], nor the results of that energy's application to the landscape, i.e. erosion, pollutant concentration and transportation and collection of harmful runoff materials.

Figure 2. Changes in Hydrology After Development



From Schueler, 1992

Figure 2 depicts the natural system's ability to even out the curve of stormwater flow rates, while also demonstrating the peaks and valleys in flow rates caused by urbanized impermeable surfaces.

Net Area Available for Infiltration

Typically with urbanization comes an increase in paved surfaces, most dramatically in parking lots and streets. However impervious surfaces are not limited to pavement. Housing and building footprints constitute area that no longer receives any input of stormwater infiltration[8]. When taken altogether, the net area that is available to receive

[7] Erosive forces, material (i.e. soils) transportation, contaminant concentration, etc.
[8] Unpaved surfaces in a city often consist of compacted soils, which have a relatively high coefficient of runoff when used in the Rational Method of computing flow rates of runoff (Appendix I).

rainwater infiltration is made up of lawns, yards, gardens, urban agriculture plots, rail rights of way, parks, boulevards and vacant sites, i.e. brownfields. This does not even include the unpaved sites with compacted soils that usually have a coefficient of runoff[9] ranging between 0.4 and 0.8[10] (Marsh 1998).

People primarily use private automobiles and truck transports to move themselves and goods around in North American cities. Paved road networks in cities are elaborate and extensive. As greater numbers of people and larger quantities of goods require movement within a city, more intricate and tightly woven networks of streets and transportation corridors are built. All of this amounts to drastic overall increases in net impervious surface area. Unfortunately, paved streets generate most of the urban stormwater runoff (Condon & Isaac 2003). As well as generating large quantities of stormwater runoff, highways are widely considered to be a major nonpoint source of pollution (Thompson et al 1997).

Consequences of Increased Stormwater Runoff

Typically with urbanization and densification (see section Low and High Density Developments for further discussion) comes a corresponding increase in pollutant concentrations in the urban stormwater runoff (Arnold & Gibbons, 1994; France, 2004). This is due to the increased presence of industrial equipment and waste, higher automobile traffic, increases in human waste, presence of contaminants from garden/lawn runoff and commercial sources. The pollutant aspects of urban stormwater runoff are:

- pathogens (disease-causing micro organisms);
- heavy metals;
- hydrocarbons and petrochemicals;
- rubber;
- chemical contaminants;
- fertilizers;
- pesticides;
- sediments;
- other pollutants;
- debris.

[9] According to the 'rational method' as listed in the equation in Appendix I.
[10] See Appendix I for table of coefficients of runoff.

These are inputted to receiving water bodies (Schueler, 1987; Kollin, 1995; Lampe et al, 1996; Burton & Pitt 2002; Gaffield et al, 2003). The type of runoff contamination corresponds with the occupying land use and its material composition. For instance, petrochemicals from asphalt shingles on roofs. Synthetic organics are most concentrated in stormwater runoff from roofs, CSOs, and local creeks (Burton & Pitt 2002). Highway surfaces, streets and parking lots show highest rates of petrochemical and metal-laden runoff (polycyclic aromatic hydrocarbons [PAH]) and also take up relatively large areas. Because they stretch over vast distances, the aggregate effect of highways and freeways, per capita is very high (Thompson et al 1997; Burton & Pitt 2002). This, however, is simply a reflection of our intense reliance on the automobile. See **Table 2** for a breakdown of pollution constituents form roadways.

Table 2: Pollutant Constituents of Stormwater Roadway Runoff

Constituents	**Primary Sources**
Particulates	Pavement wear, vehicles, atmosphere, maintenance
Nitrogen, phosphorous	Atmosphere, roadside fertilizer application
Lead	Tire wear, lead oxide filler material, lubricating oil, grease, bearing wear
Zinc	Tire wear (filler materials), motor oil, grease
Iron	Car rust, steel structures, engine parts
Copper	Metal plating, bearing and bushing wear, engine parts, brake line wear, fungicides, insecticides
Cadmium	Tire wear (filler material), insecticide application
Chromium	Metal plating, engine parts, break lining wear
Nickel	Diesel fuel, gas exhaust, lubricating oil, metal plating, bushing and brake lining wear, asphalt paving
Manganese	Moving engine parts
Cyanide	Anticake compound (ferric ferrocyanide, sodium ferrocyanide, yellow prussiate of soda) keeping icing salts granular
Sodium, calcium, chloride	Deicing salts
Sulfate	Roadway beds, fuel, deicing salts
Petroleum	Spills, leaks, lubricants, antifreeze, hydraulic fluids, asphalt surface leachate
PCB	Spraying, atmospheric deposition, catalyst in synthetic tires

Adapted from Burton & Pitt 2002

During periods of high peak flow off impermeable surfaces, or during "flash flooding", stormwater runoff will contain larger concentrations of pollutants, combined sewer overflows[11] are activated, valuable fish habitat will be lost[12], natural pollutant recycling systems will be overcome and aquatic populations will be directly threatened. Initial rains also trigger the "first flush" of high concentrations of contaminants off surfaces.

As we now see, the consequences of impervious surface runoff in urban watersheds are felt in many different ways, many of which can be quantified[13], though of equal importance are those that cannot[14]. Harbor (1994) discusses some of the methods available to planners and designers in predicting and estimating the hydrological changes that certain types of land use will cause.

The downstream effect is usually the greatest, however the loss of the water-retention functioning in the soils of cities is of great concern (Booth & Leavitt, 1999). Not all soils retain water in the same way. Some are highly effective at holding onto water, while others are hydrophobic. Soils change over time with compaction, physical/mechanical disturbance, exposure to chemicals, loss of organic components, etc.. Many of these changes are irreversible, others would at least require some form of remediation. As I will expand on later, this inflexibility of outcomes can be explained by a discussion on path-dependent decision-making based in a linear, reductionist way of seeing the world.

In the mid 1990's, the United States Environmental Protection Agency (EPA) reported that the diffuse form of urban water pollution was the most severe of all sources. The nonpoint source water contamination that is a result of urban impervious surface runoff was the leading threat to water quality. The contamination is attributed to surface runoff from stormwater flowing off impervious roofs, soils (compacted or otherwise), concrete pavement, asphalt, etc. (Arnold & Gibbons, 1996). By 1999 the US EPA put into effect its National Pollutant Discharge Elimination System (NPDES) for smaller municipal and

[11] See section entitled Combined Sewer Overflows.
[12] For example, salmon and trout spawning grounds in gravel beds.
[13] Average contaminant volumes per ha of given surface type.
[14] Non-quantifiable turbidity, transportation of materials, erosive potential, with associated 'external' costs.

large development SWM. The guidelines within this permitting system are strict and demand drastic decreases in pollutant generation and discharge off city surfaces (Coppes 2002) and guaranteed protection of surface water and BC's are not as comprehensive.

"Is this all really a problem?" you ask; why is it important for us to worry about the precipitation that falls on our urban centres? The answer lies partly in the rivers that flow through or under[15] our cities, in those marshlands in the city's lowlands that have not been filled in, in our depleted groundwater and in the coastal zones that serve our fisheries and act as such rich postcard material (Gootilleke et al 2005). When huge volumes of water are annually shed off the city's impermeable surfaces, groundwater infiltration is drastically diminished, natural waterways are the recipients of the increased discharge and accordingly, instances of flooding are on the rise (Li et al 1998; Rowney 1999). Think also of the polluted water bodies, the decreased groundwater recharge, the increased erosion of existing streams and rivers, the burying of fish-bearing streams, the rising levels of sedimentation and the decreases in fish stocks and other biodiversity in all our water bodies (McHarg 1969; ULI 1975; IAHS 1977; Herricks 1995; Li et al 1998; Pitt 2002; Rocky Mountain Institute 2005).

These pollutants are of major concern, accounting for just under half of the contamination of US lakes and rivers in the mid 1990's. This nonpoint source pollution from stormwater runoff has been identified as a major issue in coastal regions, as the effect that it has on these ecosystems and habitats is particularly severe (Li et al 1998). Coastal waters and their riparian zones, though "served" by regular tidal flushing, are highly susceptible to inputs of sediments and pollutants. Beach closings particularly reflect this (Board of Engineers 1953; Clapham 1981). This prompted the US EPA to finally enact legislation enforcing clean water standards for American cities (Coppes 2002).

In urban areas containing large amounts of impervious surfaces, a severe rainfall event will typically cause a flash flooding effect. The sudden input of water onto the surface

[15] Though there is a movement in planning and design to "daylight" streams that were, in the past routed underground, many of the historic drainages, streams, and rivers that once ran through our North American cities remain culverted underground.

will coalesce into a receiving system that is unprepared for the quick and massive buildup of stormwater flows[16]. We have to engineer large diameter sewer pipes to deal with this sudden onset of large water volumes. The more sudden the onset of high volume-flows, the larger and more expensive the sewer pipes. This phenomenon directly affects the pollutant loading of water bodies, as the combined sewer overflow (CSO) effect will be activated at this point. In a CSO, untreated sewage is added to the outflow during periods of heavy rainfall. When capacities of the receiving SWM system are not great enough to match the peak stormwater flows in a precipitation episode, the stormwater overflows in the pipes and mixes with the sewage, both of which then bypass treatment plants.

Combined Sewer Overflows (CSO)

Many North American cities, especially older ones, have combined sewer overflows (CSOs)[17]. Up to the 1950s, cities were still mostly constructing their SWM systems with CSOs (Pollution Probe 1996). These CSOs allow for the combination of stormwater with municipal sewage (blackwater) whenever storm sewers are pushed beyond their limited capacities (Clapham 1981; Moffa 1990). This occurs at a rate of roughly 200 episodes per year in the Vancouver Region. Data for the GVRD show that there is something on the order of 36-62 billion litres per year of mixed stormwater and sewage that spills into our region's receiving water bodies (Pollution Probe 1996; Pedersen 2000). Moreover, if end-of-pipe water treatment plants have to treat stormwater volumes as well as sewage, purification efficiencies are drastically lowered (Tjallingii 1995). Not only would we experience much cleaner water outflows from water treatment plants if the volumes they had to deal with were decreased, but the fees paid to the GVRD would be commensurately decreased as well (City of Vancouver Engineering Services 2005).

In order to separate stormwater from blackwater sewage, Vancouver has been involved in the "twinning" of the system for a number of years now, as per the *Sewers Long Range Plan*. Though this is a costly operation, it has been deemed crucial in dealing with the

[16] This type of drainage activity is typical of arid desert regions, yet is applicable here in Vancouver, as our urban surfaces have been given similar characteristics as those in deserts.
[17] Vancouver's earliest sewer systems were initially built in the 1890s.

health of coastal waters (Moffa 1990; Vancouver City staff 2004). Though the City of Vancouver engineering department isn't sure of the exact numbers, roughly 50% of the twinning has taken place, though in reality, this is likely much lower. By 1953, much of the sewerage systems had already been laid for Vancouver, almost all of which were CSOs. This was done despite consulting a sewer specialist, eliciting the Lea Report of 1914, which recommended "the principle of the separate system of sewers be adopted in the areas draining to English Bay, False Creek, and Burnaby Lake" (Board of Engineers 1953, pg. 4). However it wasn't until 1978 that Mayor and Council established a program to change the CSOs over to separate drainage systems. This initiative was for two of the three areas mentioned in the 1914 Lea Report, published 64 years earlier (http://www.city.vancouver.bc.ca/engsvcs/watersewers/sewers/index.htm)! Even today most twinned sections of pipe carry no guarantee that stormwater will not mix with sewage. The infrastructure is of such an age that it is difficult to monitor for mixing (City of Vancouver Engineering Staff 2005).

Moreover, even if the City were to complete the twinning of the system, something they are aiming to accomplish for 2050, there is still the matter of the countless private properties that have combined sewers. These properties will be redeveloped over time, during which their stormwater pipes will be separated from the sewage lines.

Low and High Density Developments

Some people have pointed out that there is a direct relationship between population density and increased percentages of impervious surface coverage over a given area. Their conclusions from this relationship are for more dispersed, low density development. In many cases, the motivation behind such statements lies in the desire to develop greenfield sites. However, it should not be believed that the **per capita** percentage of impervious surface is higher in the more dense urban form (around 150 dwelling units per hectare) than it is in the less dense (Rowney 1999; Gaffield et al 2003; Goontilleke et al 2005). In fact, within the city it is generally the opposite. There is a negative relationship between density and per capita amounts of impervious surface. The implications are that lower density developments have a higher per capita stormwater generating potential than do high density land uses (France 2002).

For instance, a typical suburban development of cul de sacs and large-lot, single family detached homes. Maximum lot sizes range from 785 m^2 to 2,023 m^2 (Wexler 2004). The densities may range from 2.5 to 9 dwelling units per hectare, or from 4 to 20 people per hectare. At first glance it would seem that from a SWM standpoint, this type of land use would be highly advantageous; there is ample open space for rainwater infiltration. However, this suburban style of low density development is also accompanied by large malls, huge parking lots and vast kilometers of roads[18], etc. (Garreau 1991; Duany 2004; Charter on New Urbanism 2005).

Per lot impervious surface percentages are roughly 40%, or from 314 m^2 to 809 m^2. Based on 8 metre road widths with 1 metre sidewalks, each hectare of lot development would be accompanied by 2,000 m^2 of adjacent impermeable paving. At 9 dwelling units per hectare, there are roughly 222 m^2 of adjacent paving per dwelling. Adding both the local and regional road networks serving the development and, depending on proximity of nearest amenities, there can be many hectares of paved impermeable surface per person in this type of development. This does not even consider the typical suburban style mall or big-box store providing amenities. These development are assigned a coefficient of runoff of .9 to 1.0, meaning that 90-100% of the rainwater falling on them is turned into stormwater overland flow or runoff (Marsh 1998).

In high-density developments of up to 150 dwelling units/hectare, per lot impervious percentages are from 95-98%, or from 63.3 m^2 to 65.3 m^2 per unit. If we assume the same amount of impervious adjacent paving for road and sidewalk, there are another 13 m^2 of impervious surface per dwelling, bringing the total to 76.3 to 78.3 m2 per dwelling unit in a more dense neighbourhood. This of course does not take into account other local or regional roadways, but because of business location analysis, guided typically by Central Place Theory (Von Tunen and Christaller in Pacione 2001), amenities are

[18] These, in turn are a serious nonpoint source of pollution. See Thompson et al 1997, for more details.

generally located much closer to high-density clusters. This decreases the amount of road space required per person. All-in, the per person amount of impervious surface is dramatically higher in low-density developments than in higher density neighbourhoods.

All of these paved features are impermeable to rainwater, resulting in a larger impervious surface area per capita at the regional level than the more dense urban form (Gaffield et al 2003). At the individual lot level, there is more pervious surface, however the nature of this type of built form dictates a much larger percentage of paved surface per person than a more dense, tight urban fabric. There are much larger and longer roads that are constructed, as well as the hectares of parking lots for the corresponding commercial activities.

It is true that in a **sensitive** watershed it is often better to have fewer people occupying the space at low densities (McHarg 1969). That being said, it is also true that in a **sensitive** watershed it is best to have no people occupying it whatsoever (Page 1987; Grant et al 1996; France 2002). Many low density greenfield developments in this region take place in sensitive watersheds, thus nullifying the argument for the lower density built form. The arguments from people in favour of low density developments as attractive SWM sites, simply do not hold...water.

Contemporary low density developments require vastly greater amounts of infrastructure per capita. Because the inhabitants of this type of land use are more diffuse across the whole area, it is more costly to service the stormwater with a centralized treatment plant. The cost per capita in infrastructure provision (see **Chapter 2.1**, section ***Costs*** for thorough breakdown) increases commensurate with overall length of sewer infrastructure, as does the aggregate amounts of stormwater runoff and associated pollutant levels (Grant et al 1996; Rowney 1999; Coppes 2002; France 2002).

2.1 The Underlying Problems

"*Doubt is not a pleasant situation, but certainty is absurd*".

Voltaire

The Mechanical Reductionist Worldview

The typical human response to managing stormwater has been informed by a Newtonian (reductionist) analytical framework (Capra 1982; Rifkin 1989; Iyer-Raniga & Treloar 2000; Moffatt 2001). The worldview of mechanistic science comes out of Sir Isaac Newton's theories, but is based in thinking roughly 400 years old. Probably the foremost catalyst for the development of this worldview was Francis Bacon, whose work, the Novum Organum of 1620, laid the groundwork for the movement away from positing the world as chaotic and disordered. Everything, it was argued, became ordered by mathematics, as Renee Descartes' work shortly afterwards demonstrated to the world. For Descartes, order and measurement were the ultimate ways of seeing the world. He tells us that the general science that would address issues of order and measurement "...was called universal mathematics. Such a science should contain the primary rudiments of human reason, and its province ought to extend to the eliciting of true results in every subject" (Rifkin 1980, pg. 35).

Newton went further in developing his three laws of mathematics (physics), which described all material in motion in the universe[19]. Through these "laws", human beings were given the 'power' to determine exact mechanical motion of materials (Rifkin 1980). Out of this belief in mechanistic science grew a hubris that told us all things in the natural world could be reduced to numerical equations, which could then be manipulated to our advantage. This belief is still shared, mostly unconsciously, today by many of the people on this planet, certainly the vast majority in the western world.

Thus the nature of our cities is reflective of this fundamental aspect of our worldviews. This extends into the way that we approach SWM; instead of managing the source (recall

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[19] Newton's three laws are as follows: 1. A body at rest remains at rest and a body in motion remains in uniform motion in a straight line unless acted upon by an external force. 2. The acceleration of a body is directly proportional to the applied force and in the direction of the straight line in which the force acts. 3. For every force there is an equal and opposite force in reaction (Rifkin 1980, pg. 36).

the sources of stormwater are our cities' impervious surfaces), we try to mitigate the outcome. Instead of understanding the whole system, we try to control a single, troublesome variable. Our contemporary rational model of SWM dictates a linear throughput approach to rainwater by engineering large scale pipe and channel networks with high enough flow capacities to meet design storm criteria (**Figure 3**). The system is based on throughput of the stormwater out of the city and views rainwater as a waste.

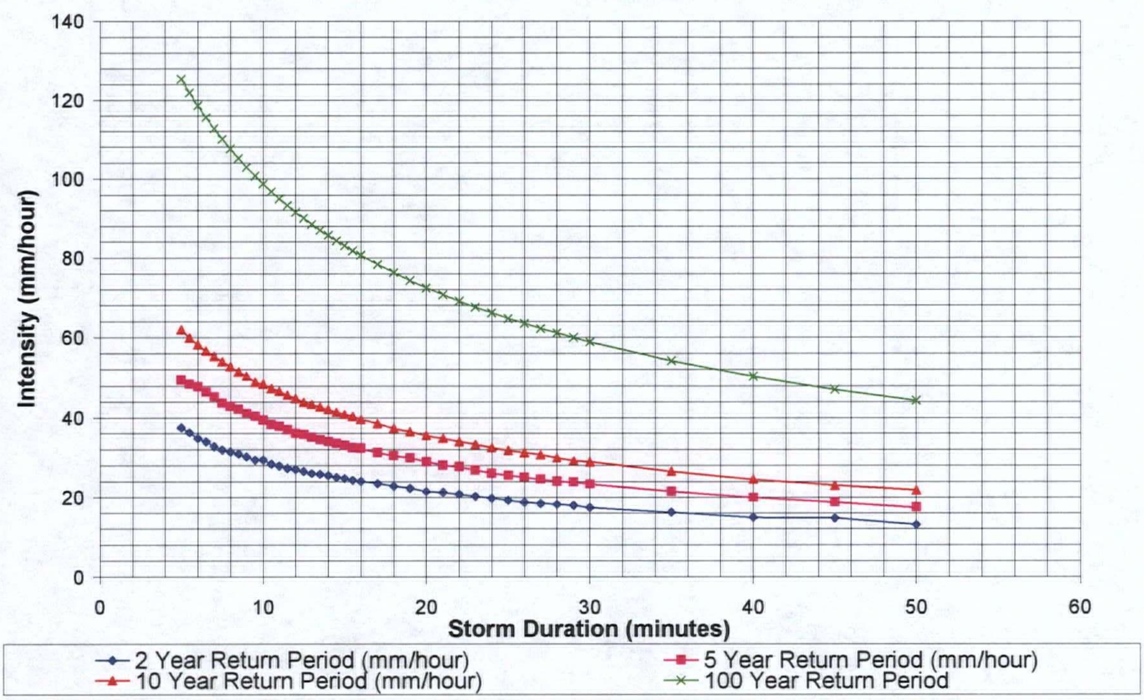
The City of Vancouver laid the earliest sewers in the region in 1890, though full-scale development did not begin in earnest until 1914 (Board of Engineers 1953). Though intentions were admirable back in the early development of sanitary sewage and wastewater systems (Clapham 1981), these large-scale infrastructure throughput systems now cause problems that are beyond the capacity of the natural environment's coping structures. To a degree this is an issue of scale and growth is an exacerbating factor. Still, the reductionist, throughput framework itself is the root of the cause.

One of the most interesting aspects of this discussion is that a survey published in 1953 for the ***Vancouver and Districts Sewerage and Drainage Boards*** talks of the "inestimable value" of the receiving water bodies around Vancouver and the "serious pollution" threatening them (Board of Engineers 1953, pg. 2). When the report was published, the SWM convention was year-round combined sewerage systems. Even then, however, people were starting to notice that the receiving waters could become polluted as population grew and sewer use increased. This 50 year-old survey describes the positive relationship between rising amounts of impervious surfaces, population growth and densification to increases in stormwater runoff. Tellingly, the report advocates for an increase in infrastructure spending and construction of end-of-pipe treatment facilities.

<u>Linear Throughput SWM</u>

The throughput model does indeed make SWM seem simple, as the goal of that exercise is to use simple parameters for the systems' functioning, i.e. merely remove the water off the surface and dispose of it as quickly as possible[20]. In order to achieve this performance standard, a SWM system must be engineered precisely, at least capable of dealing with a specific benchmark storm event. The City of Vancouver has different storm event specifications for various land uses. Residential land-use is engineered for a 5 year storm, downtown/commercial/industrial gets a 10 year storm benchmark and trunk sewers[21] are engineered to a 25 year storm (**Figure 3**). Alternately, if the goal is to mirror the complexity of the previously-existing natural system, then complex parameters must be placed on the systems' functioning. This would entail a thorough understanding and inventory of the attributes and functions of the natural system, a near impossible task.

Figure 3: City of Vancouver Rainfall Intensities



From City of Vancouver Engineering Staff 2005

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[20] Though still a challenging task, these simple parameters do not take into the account the complex interactions of the natural environment and any consequences outside of the parameters will go unforeseen; an externality of the system.

[21] A trunk sewer serves a tributary or catchment area greater than 100 acres.

There are many high-performance demands on SWM in municipalities, Vancouver included. Currently, these demands are based on the speed and ability of the system to remove the water that falls on the city's surfaces as fast as possible. The idea is to eliminate as much risk as possible. This task is possible in the short term given the money, energy and materials necessary, but what about sustaining those huge physical infrastructure networks upon which the system rests? Truly the engineering feats of the 20th century are to be wondered at. No less wondrous are the enormous costs for financing these same engineering marvels. However building it once is one thing, but maintaining it over the lifetime of the city is another prospect entirely, assuming that we intend to sustain cities beyond our lifetimes. ***Maintaining the system's physical structures is absolutely dependent on continuous inputs of materials and energy with no end to the cycle***. The diminishing returns in such a system lead to unsustainable resource requirements. By definition, a system based on continuous growth is biophysically unsustainable on a resource-finite planet, let alone financially viable.

Costs

Municipalities bear high costs of building, maintaining and continuously upgrading SWM infrastructure. The City of Vancouver, like any other city, must address the sustainability of this issue. The traditional systems of managing stormwater are very expensive, rely on intensive inputs of materials[22] and energy[23], and are ineffective at mitigating the destructive potential of increased peak/overall flows and the pollutant contamination of rainwater runoff. Addressing the pollution requires costly, large-scale 'end-of-pipe' treatment plants, which the city neither needs, if stormwater is managed at the source, nor according to city of Vancouver staff (Anonymous 2004), can afford.

Currently in Vancouver, infrastructure renewal operates on a hundred year cycle, meaning that every year 1% of the stormwater infrastructure is replaced at a cost of roughly $36 million (Vander Ploeg 2004). This means that, in theory, there is never any

[22] Materials, which themselves, are highly ordered and require large amounts of energy to transform into useable forms, i.e. large-diameter concrete pipes, steel pipes, girders, asphalt and concrete paving, etc..
[23] Repairing large-scale pipes, gutters, drainages and the overlaying roads are energy intensive processes.

aspect of the infrastructure older than 100 years (see **Table 3**). By extension, it also means that Vancouver will be renewing this physical infrastructure in perpetuity unless more sustainable options can be developed.

Table 3: Age of Sewerage Infrastructure in Vancouver

Years of construction	Length (km)	Length (%)
Pre-1930	675	38
1930-1959	565	31
1960-present	565	31
Total	**1,805**	**100**

Adapted from the City Of Vancouver Website

Will the money exist in the next several decades to perform this task? In the allocation of scarce resources, it is irrational to defend spending money on problems that can be solved through alternative planning and design. Will the fossil fuels required to do the work of repair, renewal and expansion always be available and affordable? No, fossil fuel energies are finite. Global sources of the most condensed forms of fossil fuels, petroleum and natural gas, are peaking in production and are projected to decline in production within the next 10 years (Deffeyes 2001). On a finite planet, will the raw material inputs always be available? Rational analysis tells us the answer is no. Though with recycling of materials we can draw out the length of time that many of the required materials will be available, the second law of thermodynamics dictates that this is a losing battle Mayumi et al 1999). Every time materials are recycled, a percentage is lost through energetic inefficiencies in the restructuring process[24]. Materials cannot be recycled in perpetuity, as their structures will eventually break down (Mayumi et al 1999, pg. 143).

Of course there is a direct correlation between dollar costs and thermodynamic limitations on recycling of materials. Because new materials are needed for reconstruction and repair of existing SWM infrastructure, costs are relatively higher than if these materials could be reused/recycled.

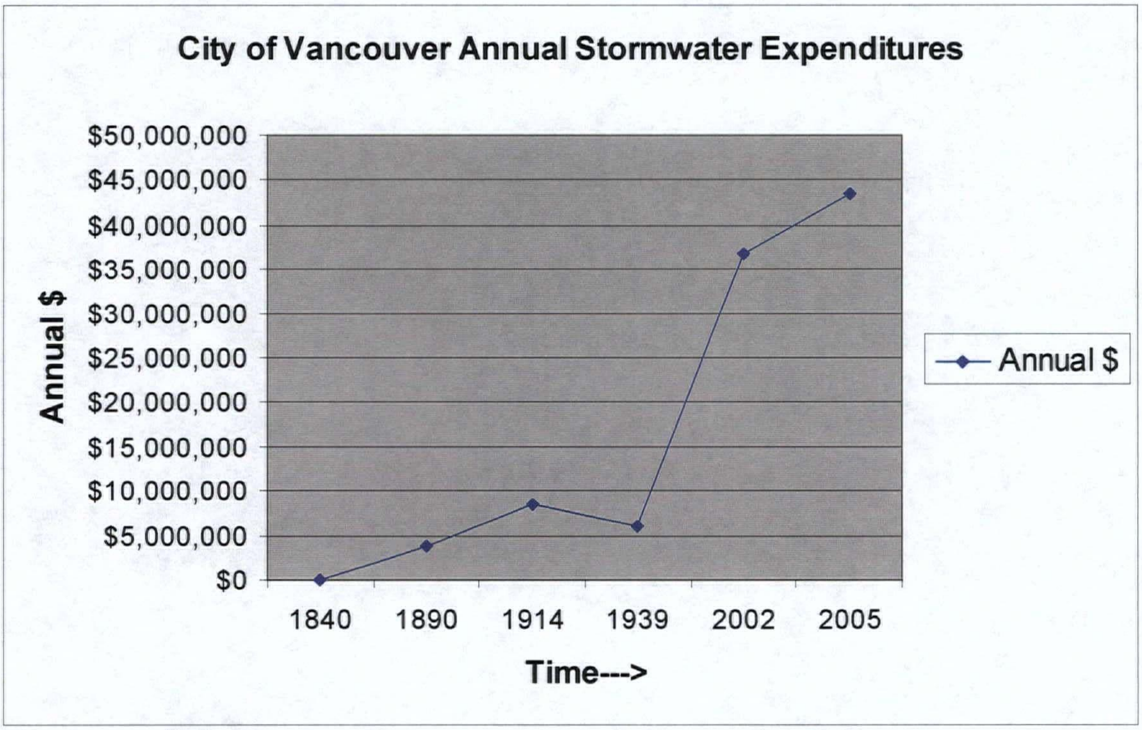
[24] There are also high energy costs of recycling these materials, the source of energy for which is non-renewable.

With the SWM 100 year cycle of reconstruction, scarce resources (dollars) are allocated to this ongoing process on the assumption that the current SWM system is the most effective method of removing the "wastewater" that falls on Vancouver as precipitation. This falls at an average rate of roughly 1,285.7[25] mm per year, 46.2 mm of which falls as snow (according to Environment Canada, the peak single day rainfall in Vancouver occurred in 1935, where 94 mm of rain fell on the city). Replacing municipal sewerage infrastructure in 2002 alone cost $36,819,825 or 4.3% of the city's total spending in that year of $856,275,000 (Vander Ploeg 2004). The City of Vancouver projects that this figure will explode over the next decade as more and more of the aging infrastructure comes online for replacement (see **Table 3**).

Let us look at infrastructure renewal and spending requirements in the future. Roughly 69% of all stormwater infrastructure, or 1,240 km will have to be replaced in the next 50 years, 54% of which will have to be done in the next 25 years. Because the infrastructure was not built at the incremental rate of 1% per year, which, at a lifetime of 100 years, is the annual rate at which it must be replaced, we are now faced with an overload of crumbling stormwater infrastructure. If all factors remained constant at today's values, national annual inflation would be 2.4% (Bank of Canada 2005) and construction costs would increase in Vancouver at roughly 4% per year. Given this scenario, if the city were to maintain infrastructure renewal plans at present levels, costs will rise, at minimum, some $2,250,009 next year alone. However, none of the contributing factors are actually constants. Percentages of infrastructure to be renewed will increase in the near future, inflation is rising (the phenomenon of peak oil is projected to compound this), construction costs in Vancouver have increased rapidly in recent years and petroleum costs are a major unknown. Of all of the aforementioned variables, the cost of fossil fuels is the most crucial to note. I will discuss this in the following section.

[25] Measurements taken at Vancouver city hall.

Figure 4: Vancouver Expenditures on Stormwater Infrastructure



From Vander Ploeg 2004, City of Vancouver, Engineering Department: http://www.city.vancouver.bc.ca/engsvcs/watersewers/sewers/index.htm **and the Consumer Price Index. Dollars are in 2005 equivalents.**

To replace the stormwater sewer pipe infrastructure in Vancouver will cost the City's Sewer's and Drainage department from $1,000 (residential, 5 year storm sewers) to $2,400 (heavy commercial, downtown, 25 year storm sewer) per linear metre (Shiel 2005). This cost is for only the sewer trench and the laying of the separated storm and sanitary sewers[26] and does not reflect the costs of replacing road surfaces.

The overlying roads are paid for directly by the Sewers and Drainage department and range from $22 m^2 and go up to $115 m^2 (residential is $46 m^2, next level up is 62 m^2 and arterial roads are $115 m^2). The cheapest option of $22 m^2 is based on a large scale (>1,000 m^2) operation, whereby the costs are shared between the Sewers and Drainage and Roads departments. Furthermore, concrete sidewalks are an extra $55-$143 m^2,

[26] No CSOs are being installed at this time, only "twinned" sewers.

depending on the job size. In the case of a newer street being dug up for stormwater infrastructure maintenance, the Sewers and Drainage department is charged a "street degradation fee" by the roads dept (Marino 2005).

Total costs of replacing or installing the SWM infrastructure for a typical residential street, 100 metres in length and 8 metres wide, including 3 metres for sidewalks on both sides would be $100,000 for pipes, $368,000 for roads and $15,500 for sidewalks for a total of $484,500. Let us then say that the 900 km of CSO were to be rebuilt as separate sewer lines, the lowest possible cost, if done at present values, would be $900,000,000 for the pipes alone. The cheapest road rebuilding overtop of the new twinned pipes would be $158,400,000, for a total of $1.584 million at today's costs! Keeping in mind that this cycle of rebuilding 1% per year is repeated for as long as this system is in place, we begin to see the unsustainable costs incurred through this type of SWM system.

Peak Oil

There is an underlying issue of major importance to this research that will, in the not-so-distant future determine the outcome of the debate on sustainable SWM infrastructure. This issue is the approaching peak of global oil production. This is not to say that global petroleum supplies (and production) will run out next year, but there is no question that it is running out. Many of the top petroleum geologists claim that global oil production is peaking right now, will peak later this decade, or will peak sometime within the next 15 years (Deffeyes 2001; ASPO 2005; Goodstein 2004; Simmons & Co. 2005). Regardless of the exact year in which the peak (or plateau) will occur/is occurring, 2005 has seen huge leaps in oil prices. A report issued by investment firm Goldman Sachs in late March, claimed that there is an immanent "super spike" coming in the global oil market (BBC 2005; Goldman Sachs 2005). Most researchers link this to the lack of spare production capacity of the world's major oil producing regions. As a result, crude oil prices rose to $57.70 on March 25th, topping the previous high mark set on March 17th 2006 of $57.60 (BBC 2005).

The construction and maintenance of conventional SWM infrastructure requires concrete and steel materials, as well as the heavy machinery to perform the work. The asphalt roads overlying the SWM infrastructure in our cities must be replaced after the infrastructure below has been repaired or rebuilt. Many of the materials must be shipped to Vancouver, the costs of which are dependent on cheap oil prices. All of the aforementioned materials and processes are extremely petroleum fuel-intensive. As global oil production peaks, the cost of maintaining the SWM infrastructure increases commensurately with oil price increases.

There is clear consensus among those who are researching the issue that world oil will be peaking shortly. Knowing this, the further we travel down the Newtonian path of dependence, while building the linear throughput SWM systems, the harder it will be for us to change in reaction to skyrocketing petroleum prices. In a context where the future of oil is as unknown as it is today, maintaining the status quo of SWM thinking not only makes our cities less secure and unsustainable, it is irrational.

Path-Dependence and Unsustainability

As noted earlier, the current paradigm for managing stormwater comes directly out of the Newtonian, reductionist way of thinking. This conceptual framework isolates problems and deals with them through simplified, linear solutions (Capra 1982; Rifkin, 1989; Iyer-Raniga & Treloar 2000; Moffatt 2001). This way of addressing the 'problem' has been entrenched through many years of similar decision making. In short, today's approach is "path-dependent" on a paradigm that shaped the earliest decisions on SWM and city building. Over time, the Newtonian worldview continued to guide people's visions and methods of city building (Capra 1982; Rifkin 1989). Habit has since reaffirmed and solidified the traditional way of thinking, illustrating the self-referencing nature of contemporary decision-making structures and institutions (Pierson 2000).

The concept of path-dependence, also referred to as "increasing returns", describes the inflexibility of the processes in decision making that are based on incomplete knowledge, or (initial) random actions (Pierson 2000). Pierson sheds light on the nature of path-dependent decision-making that leads to outcomes that are difficult and costly to reverse. Path-dependence suggests that small, initial decisions, plans, etc. lead, over time, to larger outcomes, through an almost auto-catalytic process of self-referencing. Once certain conventions, "institutions[27]" are in place, they guide decision-making down a path from which it becomes increasingly difficult to steer away. These decisions have eventually lead to the city-building that we experience today.

As Pierson states "the costs of exit-of switching to some previously plausible alternative rise" (2000, p. 252) as the institutions become engrained, or, in the case of SWM, the physical structures of our cities become entrenched. This is not to intimate a deterministic outlook in planning, but is more to explain the institutional inertia with which we are faced in trying to move towards sustainability. Change is possible, but cannot occur until we have understood both the need for it, as well as the historical forces (path-dependence) that resist it. For instance, we already know that both the Lea Report of 1914 and the Board of Engineers Report of 1953 advised that the storm sewers serving areas around False Creek and English Bay should NOT be CSO. Yet, all of those sewers built in those areas were indeed CSO. The City of Vancouver website states that "it was accepted practice to construct combined sewers which discharge directly into waterbodies via outfalls" (City of Vancouver Engineering Services 2005). This is a clear example of the cost of exit of path-dependent planning. Though decision-makers were advised not to construct CSOs, they followed the simple conventions at the time, ignoring better advice. We are now burdened with the cost of exiting the path. Today's costs of exit are extraordinarily higher than they would have been to construct the separate system in the first 40 years of the 20th Century. This should be a learning example for understanding and breaking unsustainable path-dependent decision-making.

[27] Institutions are the agreed upon 'rules' of action within organizations. They can be explicit or implicit; formal or informal.

The Rational Comprehensive Model

By predefining the problem of SWM through the path-dependent Newtonian worldview, the rational comprehensive planner, engineer or decision-maker of today sees only the 'optimal solutions' that institutional inertia has placed before him or her. The rational comprehensive planning worldview is guided by logical steps and separates analysis from decision-makers (Wachs 1985). In this model the analyses of the SWM problem are entrenched in the historical path of dependence and guided, logically, by institutional inertia.

The political decision-maker is not likely, unless predisposed, to be aware of the parameters, or underlying institutional inertia that has guided the analyses put before them and so cannot act outside of those constraints. Typically then, a decision-maker will follow the recommendations from the analysts' logical steps of problem definition and analysis (Wachs 1985). In turn, these analysts are confined by the "predefined" problem, which has lead to increasing returns of SWM operational and performance guidelines. The rational comprehensive planner then, sees only the alternatives suggested by these types of analyses, from which logically flows, the contemporary models of SWM.

<u>Entropy and Dissipative Structures</u>

But why should we worry about having to rebuild that 1% of the SWM system every year in perpetuity? What makes this unsustainable? Well, a city is an open system insofar as it receives both energy and material inputs from beyond its boundaries. So long as there is sufficient energy and materials that can be brought in to act as inputs to the SWM system, the city can theoretically continue to function according to its highly ordered system requirements. However, organization or structure in one anthropocentric system comes at the expense of disorganization elsewhere, i.e. imposing structure in one place requires an energy input from somewhere else, much like balancing a scale (Mayumi 1999). The second law of thermodynamics, the entropy law, tells us that energy can only go in the direction of useable to unusable. So if energy is used to create order in one instance, it must come at the expense of disorder somewhere else (Clapham 1981; Rifkin 1989; Mackey 1992).

This can be termed "metabolism", insomuch as a biological structure consumes energy and materials in order to sustain itself, while also producing less useable wastes (Clapham 1981). Giampietro & Pastore (in Mayumi 1999) go a step further, terming the anthropogenic systems of consumption and waste production "exosomatic metabolism". Through the process of consumption, the energy and materials are dissipated. Biological systems operate in this way, by taking energy and materials up from their surrounding systems and outputting the dissipated materials and energy, "wastes" back into those same systems. Systems such as these are termed dissipative structures (Iyer-Raniga & Treloar 2000; Rees 2003) and are ***differentiated*** by nature. Rees explains the second law's effect, stating that "*any* differentiated system has a natural tendency to erode, unravel, and disperse" (2003, pg.6).

A dissipative structure, such as a city, is highly complex and requires large quantities of energy to maintain that complex, ordered structure. Natural, adaptive systems are self-organizing, meaning that they develop complexity over time through a process of evolution and continuous intake of energy, e.g. the natural system of managing precipitation. Whatever system, e.g. stormwater infrastructure, is employed to replace these naturally-ordered structures will require more energy input to provide the same functions than did the previous one (Iyer-Raniga & Treloar 2000; Rees 2003). However, it will fall on a spectrum of energy requirements.

For example, picture the sloping south west coast of BC. At one time, prior to human intervention, the mountains sloped gently into the ocean and were covered by mature forests, many streams and several larger rivers[28]. The watershed's drainage and vegetation characteristics were influenced over time mainly by the area's rainwater, snow, and climatic factors. The drainage patterns were developed by the frequency and

[28] These characteristics developed over long periods of time in response to geomorphological and climatic forces.

amounts of rain that fell on them. The vegetation that grew there, matured in relation to the local climate, developing in response to precipitation levels and temperatures, i.e. storms, hours of sunlight, average rainfall levels, monthly temperatures, etc.. The geology of the area constrained the types of drainage that could take place, resulting in patterns of best fit determined by the landscape. The energy that went into shaping these systems came from the sun (vegetation and weather patterns), the falling precipitation (erosion and sediment transportation), geological process (orogeny, plate lifting). The inputs of energy are continuous, providing the basis for the landscape's dynamic equilibrium (Christopherson 1994).

The anthropogenic substitute systems are built, not to fit with the natural system parameters, but to assist in providing the services that our cities "require", such as flat, drained and paved transportation corridors, appropriate building sites and generally ordered impermeable surfaces. The artificial substitute structures are vulnerable to failure in instances of extreme fluctuations, tend towards dissipated states (Rees 2003) and are less adaptive to environmental change (Tainter 1995).

A relationship of dependence has been created, whereby the city requires a constant flow of inputs from beyond its boundaries. This dependency is not absolute, as the component parts of the city's systems determine the degree to which they are reliant on external inputs. Some cities, because of the systems in them (transportation, SWM, agricultural, etc.), require large quantities of material and energy inputs for their proper functioning, while others are capable of greater self-reliance. For instance, if a city has been designed primarily for transit use, the overall transportation system will be less dependent on energy inputs than if the city was more car-oriented (Duany 2002-2005: Calthorpe 2005). The same can be said for SWM (France 2004). If a city's professionals design a SWM system that requires less repair, smaller pipes, fewer sewers and no end-of-pipe treatment plants, that city will have lower energy requirements in the SWM sector. Thus, a particular city's continuous requirements of materials and energy inputs are determined by the design of the system (Funtowicz & O'Connor in Mayumi & Gowdy 1999).

Though SWM alone will not be the deciding factor of the sustainable functioning of a city, it is one component part of overall sustainability.

The Green Building movement in Canada and the US that has been gaining momentum for some time now and the newer, less established idea of green infrastructure are based on this concept of decreasing the reliance on materials and energy inputs into built structures. The USGBC and CAGBC acknowledge the importance of addressing energy requirements to building/designing sustainably[29]. They have also deemed SWM to be an important aspect of sustainable design (CAGBC 2004). The certification system of LEED acknowledges SWM in buildings by assessing LEED points for design elements that mitigate onsite stormwater (CAGBC 2004).

To further define the situation, cities function as complex systems insofar as they have negative and positive feedback loops to deal with various stimuli. Through their functioning, cities disperse energy, take in materials, and produce waste. Without a continuous input of neg-entropy, a city's system would see an overall increase in entropy. Entropy is a measure of disorder, of dispersed or unavailable/unusable energy. Neg-entropy then is the measure of usable/available energy in a system (Silver 1971; Mackey 1992). Entropic increase in a system can have many effects, one of which being inefficient functioning. If a system was unable to receive external inputs of energy and materials for some reason, it would shortly be unable to function. A system that relies on unreliable inputs of materials and energy is a relatively insecure system. It is also indebted to paying for these inputs and is at the mercy of cost increases, materials/energy shortages (Deffeyes 2001) and market scarcity[30].

Further, the city as functioning system is embedded within larger and more complex natural ecosystems at many different levels, the Biosphere being the highest. As such, the dissipated material that leaves the city system and is taken up by the surrounding

[29] To this end, the US Green Building Council (USGBA) estimates that approximately 2% of all new buildings in major cities in the US and Canada are being built according to 'green building guidelines'.
[30] This type of dependence put cities at the mercy of market whims that, sometimes arbitrarily, dictate energy and materials' pricing.

ecosystem must be taken into consideration when analyzing the functioning efficiency of a particular city. This can also be looked at on a different scale, similar to the relationship just mentioned. That is of onsite to offsite SWM. There is a relationship between the ecosystem functioning at the two levels and the interplay between the onsite and offsite SWM. There are inputs and outputs to both and inter-reliance between them.

Designing the System

Ultimately then, the responsibility for the system of any given city lies in the hands of a widely-varied group of professionals: the decision-makers, planners, engineers, and designers, i.e. architects, landscape architects, and urban designers. On one hand it is the knowledge and understanding employed by these individuals in their professions that guides the SWM systems. In another sense, it is the inertia from path-dependent actions that an already-developed city presents to those actors wanting to change it. The concept of path dependence describes how the cost of exiting a certain "path" or series of additive decisions goes up as time passes, i.e. a certain way of doing things becomes firmly entrenched (an addiction, a habitual action), rendering it very difficult to change the course, because no other way seems possible.

A contributing factor to the issue of choosing appropriate technology for urban rainwater management systems in cities is the complexity of the pre-existing natural system. Because much of the precipitation that falls on a landscape as stormwater is typically taken up through infiltration into groundwater,[31] it is very difficult to model the locations of outputs into the surrounding environment. Consequently as surfaces are paved over, the results have been difficult to predict, leading to simplified decision making. Paving, gutters, large-scale detention tanks, rainwater concentration and piping are typical types of urban infrastructure. These are typically reductionist ways of taking the complexity out of the system in an attempt to introduce order and simplicity to it. However, as I suggested earlier, any simplification to the system at one point will result in negative

[31] In typical precipitation events, much of the ground is capable of retaining most of the water. In extreme precipitation events, there will be overland flow of all water that does not infiltrate. The only other issue here is the potential damage to structures if the surrounding soil is not effective at infiltrating the water.

impacts elsewhere. This is usually manifested in increased channel flow of streams, concentration of contaminants in stormwater runoff, decreased infiltration capacity of soils, lowering of the water table, increased erosion, and negative impacts on marine life (Rowney et al 1999; Burton & Pitt 2001; France 2004).

At the time of decision-making, all factors make it seem much simpler to opt for the SWM technology that appears on first glance through the reductionist, Newtonian path-dependent lens, to be more ordered, safe and primarily, reliable[32]. It follows the entrenched-route of increasing returns, but at the cost of removing redundancy from the complex system. In a naturally-ordered biophysical system, one can find certain structures, or mechanisms that have evolved over time to mitigate the energetic effect of falling precipitation on that system. The system is self-structuring and has evolved over many millions of years into the state at which one sees it now. The precipitation inputs to the system are the direct cause of the specific structural designs in it that manage those very same water inputs. In essence, the rainwater itself plays a huge part in designing the rainwater management structures of the receiving system. Because these structures have evolved over time, they are responsive to naturally occurring extremes and fluctuations in conditions. Redundancy in the natural system means that there are multiple structures of mitigating precipitation inputs, allowing it to be more resilient.

Contrast this with today's linear throughput SWM conventions, whereby we apply a non-adaptive system of pipes and sewers to a complex biophysical landscape. In a city, we remove the redundancy from the system and eliminate the naturally-evolved structures of precipitation mitigation, leaving the area vulnerable to climatic fluctuations. There are also a whole array of new pollutant input loads that we could not predict the severity of and therefore build into our earlier SWM systems.

In managing urban stormwater, what looked early on to be the simpler route, is now winding up giving us unpredictable and undesirable consequences. Confounding the issue further, many of the negative impacts are felt in other locations, usually further

[32] Engineering of pipes, drains, networks, etc.

downstream and from a nonpoint source that is difficult to pinpoint, though nonetheless severe. The longer/further down a path of dependence our systems move, the more substantially we build on and around them and the more costly it is to detour from them.

There are fundamental issues of sustainability that must be addressed in the linear method of managing the rainwater that falls on the city. Some sustainability-based questioning gives rise to the following queries: is the stormwater management system economically sustainable? Is it ecologically sustainable, i.e. does it minimize the impact on the surrounding natural environment? Does it make use of appropriate and available technologies? What pedagogical function does it perform (Li et al 1998)? Are the required levels and qualities of material and energy inputs available over the long term, i.e. sustainable[33] levels of inputs from outside the system?

Most critically however, should be a question of whether or not this system could be made more effective at addressing all of the objectives of managing stormwater, while at the same time being integrated into planning for larger sustainability initiatives within the City of Vancouver at a minimal cost. Fundamentally, of course, it must meet economic sustainability objectives; a triple bottom-line assessment of the SWM is integral to sustainability goals. This assessment takes into account social and ecological costs, as well as the traditional economic 'bottom line'. Upon describing our present, unsustainable situation, the next challenge is to define 'sustainable development' and put it into a local context for SWM.

[33] Deffeyes describes the coming decline in peak oil production in Hubbert's Peak (1999).

2.2 Defining Sustainability

"While politicians, planner, and other write and talk about sustainability, they continue practices that undermines the sustainability of landscapes".

Grant et al 1996, pg. 2

One fundamental goal of planning is organizing for positive, dynamic response to the world's complex problems. Essentially, human beings want our civilizations to endure beyond our own years; we want them to be sustainable into the future. The specifics of sustainable development have evolved over time to take on a complex nature of their own[34]. As stated in the first chapter, my definition of sustainable development begins with dynamic and inclusive planning and actions for the betterment of all humanity that can be pursued only if these processes and outcomes are not at the expense of ecological, social, cultural, or human welfare. It must be possible to apply any and all human activities to every person on the planet. Per person shares of the Earth's natural capital must not be spent such that the spending eliminates the possibilities for future generations' planning and actions for their own betterment. The egalitarian distribution of the global aggregate of all human activities over time is defined by the parameters of sustainable development.

The historical records of homo sapiens and indeed our predecessor, homo erectus have been marked by periods of conflict over natural resources[35] (Wright 2004). In many cases, it has been access to available energy through natural resources that has allowed a civilization to order its internal structures. Building a civilization on available natural resources has been historically followed by diminished resource stocks and local environmental resilience. This is especially the case when a civilization had access only to locally-available resources. An unsustainable civilization builds itself through overuse of available resources and collapses when those resources run out (Tainter 1988; Wright 2004; Diamond 2005).

Today sustainability happens at different scales, all of which contribute to global sustainability. Cities are the locus for resource consumption today. At the city scale

[34] See appendix V for a timeline of sustainable development definitions.
[35] Resource wars are only one factor of many behind human conflict.

then, if internal functioning is unsustainable, that city contributes to a globally unsustainable system of natural resource consumption and waste production.

The natural/biophysical capital of the planet is capable of producing 'interest', the free[36] goods and services that humans live off. This natural interest can be consumed sustainably only if the processes of consumption can be shared by all humans, i.e. it is not sustainable to have one fifth of the planet's human population consume an incommensurate amount of the planet's natural interest, even if the aggregate of natural resource consumption doesn't eat into the natural capital.

One of the free services provided by the biosphere is wastewater recycling. Ecosystems have limited recycling capacities for dealing with contaminated water (Clapham 1981). The bases of ecosystems are adaptive cycles set within hierarchies (Iyer Raniga & Treloar 2000; Holling 2001). These are mechanisms in healthy systems that deal with dynamic types and levels of inputs, including waste products (dissipated materials). The hierarchy of cycles allows for "communication" between levels, such that the lower levels react quickly to disturbances and allowing the higher levels to be relatively static.

The mechanisms and redundancy in ecosystems allow for dynamic inputs of wastes, but these structures are finite in their capacity to assimilate wastes. Basically, ecosystems function by having rapidly innovating and smaller levels below larger, more slowly innovating higher levels. The larger level above is kept in a dynamic state that allows for change by the smaller and more innovative levels below. There is a sort of back and forth between the levels that allows for a "learning with continuity" to take place (Holling 2001, pg. 390). Sustainability in such a system is obvious; the system is adaptable, evolutionary in nature and self-organizing, bringing structure. In such an instance, there is fit within the constraints of the larger system. When human beings stretch the parameters of an ecosystem by introducing new waste products and consuming

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[36] These goods and services are free only insomuch as the planet does not have a monetary price tag attached to dumping raw sewage into an ocean. Sometimes there is a dollar price to pay, but it is the human economic systems that charge that by way of internalizing an "externality".

biophysical products, the ecosystem, though dynamic, doesn't have time to adapt to the new environment.

Sustainability of SWM in Vancouver

In the case of SWM, the rapid paving and impermeablization of cities has drastically increased the wastewater inputs into receiving water bodies. In many cases, this has led to the disturbance or killing of lakes and rivers. Vancouver is lucky in that one of the receiving water bodies of our city's wastewater, the Pacific Ocean, is enormous, having a correspondingly large capacity to assimilate waste stormwater runoff. There is however, a huge local impact on local marine ecosystems in the region. If Vancouver were the only city in the world inputting stormwater to the Pacific and if there were no other constraints on the natural resources of the ocean, the only impacts would likely be felt by the local ecosystems. However, as noted earlier, the global aggregate of impacts of waste inputs into and resource extraction out of the Pacific Ocean will eventually overwhelm local marine systems, pushing them beyond their historic boundaries and sending them into a "strange attractor", which may not be amenable to human existence (Rees 2001).

The particular structural features of the SWM system chosen by a municipality will determine the ecological consequences. The SWM components will also determine dollar costs to the municipality and whether or not the system is ultimately sustainable. These are crucial aspects of the overall sustainability of the city. For instance, the system cannot be sustained if it is both growing and dependent on inputs of finite, non-renewable resources. Either of the above issues should be enough to promote development of more appropriate and dynamic/responsive systems. Indeed, these issues are emerging sources of concern for municipalities across Canada and the US. The past several decades have seen some improvements to urban SWM systems, but without widespread structural changes.

The Present Contemporary System:

In sustainability planning, we try to grasp why things have gone wrong in our previous attempts at city-building, assess the uncertainty and unsustainability of our cities and suggest the framework for sustainable planning (Iyer-Raniga & Treloar 2000). In our present system:

a. The required physical inputs in our status quo SWM are based on dwindling supplies of non-renewable sources of energy (Deffeyes 2001) and materials. The structures of the SWM system dictate that developing substitutes for the materials and energy inputs is problematic and expensive;
b. We use the natural recycling capacities of the ecosystems within which the city is embedded to dispose of the stormwater outputs (waste products). The recycling and dispersal capacities of these local natural systems can and will be overcome by the large amounts of waste outputs to them (Board of Engineers 1953; Burton & Pitt 2002);
c. The value of the natural recycling capacities in point b. above are considered economic externalities and are not given a cost value when determining the bottom line of a SWM framework;
d. The stormwater sewerage infrastructure and indeed all structures within the city are subject to the laws of physics, especially the entropy law, which dictate that, in the absence of continuous repair (inputs of energy & materials), they will move from order to disorder; from high to low-energy states. These structures will also be affected by breakages, backups, resizing needs and disturbance through road construction and new building, tending towards high entropy (Rees 2003);
e. Our present system of decision-making is path-dependent, set in motion by its origins in mechanistic Newtonian thinking. The Newtonian paradigm goes contrary to complex systems' theory and concepts of self-ordering ecosystems. It is self-referencing in the ways that it influences the decision-makers who work within the system. The result is institutional inertia and it stands in the way of updating the paradigm to reflect new knowledge and understanding of complexity;

f. In light of more viable alternatives, allocating scarce resources to an unsustainable system that will only grow in size and demand is irrational.

Appropriateness

Because urban regions have widely differing ecological, climatic and cultural characteristics there is no universal approach to SWM that is appropriate to all contexts. Different municipalities may require very different SWM systems, each designed to meet particular needs. Determining what is most appropriate for a given location involves a detailed examination of the local context (McHarg, 1969; Marsh 1998; Moffatt 2001; France 2004) with a multi-criteria framework guiding the decision-making that is built around principles that are the focus of this thesis.

Every time humans impose ourselves on the landscape, we disrupt the functioning of the natural systems previously at work in that location. Good planning can minimize the disruptions. SWM systems encompass different spatial levels: the regional, the watershed and the local, or micro scales (Shamsi, 1996, Gaffield et al, 2003). The local/micro level is then broken into two areas: onsite and offsite management. If the local level is the city, then onsite management takes place at the building or parcel level, while offsite management encompasses roads, sidewalks, parks, etc.. Integrating onsite with offsite management schemes in Vancouver is difficult because of the separate departmental jurisdictions, though under one comprehensive plan is entirely possible. We must identify potential alternative SWM features, analyze their relative effectiveness, discover opportunities and constraints to implementing them and then determine the simplest and most cost-effective options.

As discussed earlier, traditional SWM has been done through engineering the proper sized pipes, so that the water can be transported off site as quickly and efficiently as possible (ULI, 1975; Hammer & Hammer 2001; France 2002). Stormwater was thought of solely as a waste and the capital costs of the system to deal with these wastes have been deemed worthwhile[37]. Only recently have the simple engineering approach and the rubric of minimum engineered standards been questioned by practitioners. The "Factor Ten" movement in engineering, pioneered by the Rocky Mountain Institute researches where contemporary engineering has tackled performance objectives without realizing the consequences of the actions (Rocky Mountain Institute 2004).

Perception: Rainwater as Resource

Typically decision-makers see falling precipitation as a waste instead of as a resource (Rowney et al 1996; Coppes 2002). Of course, viewing it as such is squandering a huge potential resource. I argue that the shift in perception from seeing rainwater as being potential stormwater (with its associated problems) to seeing rainwater as being a valuable natural resource is the base upon which sustainable thinking develops. Often, sustainable options are based in simple technologies that, once introduced, seem intuitive. For example, green roofs, rainwater detention ponds, cisterns, porous pavements, etc. are simple technologies that come out of a different way of constructing the problem.

The cases of Los Angeles and the State of Massachusetts show a change in the perception of stormwater from waste to resource. The State of Massachusetts sees rainwater as a source for irrigation, while Los Angeles now uses stormwater to recharge its groundwater for later use in irrigation[38](Coppes 2002). Simply recognizing that stormwater can be used as an inexpensive way of recharging diminishing groundwater resources is a fundamental shift in perception (Li et al 1998). Once this shift in thinking has occurred, the benefits[39] of the resource start becoming clear and alternative methods of dealing with it become more obvious and defensible. The supply of fresh water through devices, designs and structures of rainwater collection/retention costs very little compared to the dollars spent on trunk water provision (Moffatt 2001).

[37] See the Lea Report of 1914 and the Board of Engineers report to the Vancouver regional sewerage and drainage board in 1953 for a historical view of the esteem with which we have viewed these methods.
[38] Also, to ameliorate groundwater contamination through lowering pollutant concentrations.
[39] Perceptions of stormwater as resource can lead to many benefits, including, but not limited to: aesthetic water features, tools for ecological awareness and education, for use in buildings in flushing toilets, for cleaning, eventually for drinking (after onsite treatment), passive cooling, urban agriculture, etc..

Crumbling Cities

All cities' infrastructure is deteriorating at a rate that depends on several factors[40]. As the costs of construction rise, so do the costs of infrastructure renewal. The municipal spending on infrastructure in Vancouver, of which SWM systems are an integral part, is second only to that spent on "protective services" and is higher than that spent on transportation (Vander Ploeg, 2004). Much of this spending goes into maintenance of the existing system (Dreiseitl, 2004), but is also greatly affected by upgrading and upsizing requirements to keep pace with development.

The water falling on land has erosive and transportation potential. Gravity pulls that water towards the lowest altitude. As it flows over land it moves material, etches the land with its passage and is purified in the process, leaving behind the landscape that we experience. In an untouched area, these forces have been balanced out over millennia in order to achieve the dynamic equilibrium that is present today. Disrupting the system requires that an input of energy equivalent to or greater than that stored/represented in the physical structures of the natural system. So long as the disruption continues, the input of materials and energy is necessary. Moreover, the new system must establish a new equilibrium with the energy potential of the stormwater coursing through it.

[40] Levels of usage, construction materials, design, and environmental factors such as soil conditions, temperature fluctuations, presence of freezing, thawing, etc.

2.3 Limitations & Scope

"Theory as such is of no use except in so far as it makes us believe in the coherence of phenomena". **Goethe**

This research began out of a desire to pursue an understanding of how the concepts of 'impermanence', 'entropy' and thus biophysical 'sustainability' are brought into city-building by planners, decision-makers, architects, engineers and designers. I decided on the City of Vancouver as a model city in which to illustrate these ideas. There was one central question that evoked the investigation into sustainability here. Reading current historical investigations prompted me to ask "what compels us to ignore the historical record, making decisions that, eerily, are larger scale repetitions of previous mistakes?"

Looking at biophysical sustainability in the context of urban planning, I saw that in infrastructure decision-making, it is well known that the system 'falls apart' over the years unless it is repaired[41]. If this concept is understood, it would stand to reason that Laws of Thermodynamics would be a major, explicit consideration for the long-term design of urban systems, though they are not. The human time horizon of several decades does not allow room consideration of systems of city-building that can be sustained beyond the next generation. The more path-dependent our methods of infrastructure design are, the more difficult it will be to take alternative directions. I see this as an opportunity to begin the shift now and want to know where and how that shift may take place. I bring these concepts into the discussion in the Findings chapter.

Working from broad concepts of sustainability, I narrowed the research to look at one specific aspect of infrastructure in Vancouver, SWM. This component of urban planning is a good case study of potentially sustainable city-building, particularly related to my early work in that it deals essentially with energy in systems. What is water falling from the sky if not potential energy? And that water, when on the ground, holds tremendous energy as it flows across the landscape as stormwater. SWM systems must be designed with a comprehensive understanding of this.

[41] An implicit input of energy and materials

Because SWM is so highly connected with almost all aspects of how cities are built, where cities are located, how transportation is planned and managed, the predominant building materials used, the dominant paradigm of decision makers, the ages of cities and so many other variables, the task of determining a sustainable SWM system for the City of Vancouver, or any city for that matter, is multi-faceted.

In order to bound the thesis, I touch on several issues that warrant further exploration. I have identified these as: organizational change, sustainability-based decision-making and politics, the role of SWM features as pedagogy, the role of cultural epistemologies in determining path-dependence, how path-dependence has affected Central Area Planning practices.

Research Questions

The foregoing problem definition led to the following research questions:

1. What criteria should be used to assess the sustainability and effectiveness of stormwater management systems?
2. What sustainable and effective stormwater management options are available to the City of Vancouver and what are the opportunities and constraints to implementing them?
3. What are the best means of implementing sustainable and effective stormwater management options in the City of Vancouver?

I will focus mainly on onsite SWM. Onsite management is one aspect of the complex SWM system for Vancouver, but one that was highlighted through various conversations and interviews in the development of this thesis. The onsite management approach is one integral aspect of a larger holistic strategy and focuses on the lot or parcel level of SWM.

3.0 Methods

a) Literature Review

I conducted a thorough literature review of the current qualitative research in these fields of inquiry to begin answering the research questions. Of most use was the inquiry into the problems and best management practices. This provided me with a strong understanding of the problems facing municipalities, which led to defining the most appropriate questions (research and interview) to pose. Without the background literature review, I could not position the problem in such a way as to ask effective questions.

I pursued a further literature review in order to provide partial answers to my research questions. This investigation was used primarily to follow-up on the answers provided to me during the interviews, as well as to position the interviewee responses within a larger, shared context of other municipalities and research. The linkages and commonalities between the Vancouver context and those of other jurisdictions was of great value to understanding the solutions that would best address the research questions of this thesis.

b) Informational Interviews

In order to conduct the interviews, I contacted municipal offices in several municipalities through an introductory letter, explaining the nature of my study and its application. In the letter I requested volunteers for participation in my thesis research. I received very positive feedback from staff in the City of Toronto, the City of Vancouver and Portland Oregon. Using the volunteer contacts, I coordinated with the individuals willing to be interviewed and subsequently conducted 21 initial telephone and in-person interviews[42] with professionals working in:

- Planning (2 in Toronto, 2 in Portland, 2 in Vancouver);
- Design (1 in Vancouver, 1 in Toronto);
- Engineering (4 in Vancouver, 1 in Toronto);
- Research: NGO, professional and institutional (5);
- Architecture (4 in Vancouver).

[42] See Appendix III for a interview protocols.

I chose the Cities of Toronto Ontario and Portland Oregon because they have both taken strong steps towards understanding large-scale, integrated SWM. Investigating the practices undertaken by those cities shed light on many of the options that exist for Vancouver. Though not 'in-depth case studies'[43], the overview of the SWM management strategies, best and worst practices and policy options for these two municipalities is an effective way of gaining insight into the SWM problem (Stake 1995). These interviews provide information about organizational directions, best/poor practices, policy implementation and the processes of change and adaptation (Robson 2001).

Because there are many aspects of SWM that typically go unquantified in municipal planning, the values that professionals place on certain outcomes and strategies are important transferable lessons. These data are often found in anecdotal format. This is especially true in the realm of political decision-making; the expenditure and savings of "political capital" are of great concern to politicians (Price 2005). Key anecdotal and narrative persuasion issues in the interviews (Brandell & Varkas in Thyer 2001) are obviated through this research by the relatively high value of anecdotal information in this field and by the structure of the interview questions. I was sure to make special note of the narrative and how the anecdotal information related to the direct answers to the interview questions.

These interviews were crucial to building an understanding of how the professionals working in the field actually deal with the issues of SWM, both in Vancouver and abroad. Interviews with professionals working outside of Vancouver proved especially useful in determining best practices and organizational learning from other contexts.

I employed three types of interviews, depending on the situation. They are the open-ended interview (used least often), focused interview and structured interview. The open-ended interview was geared towards investigation into an individual's perceptions of the SWM problem. This style is useful to this study, as it facilitates the discussion around organizational opportunities and constraints. Focused interviews were used in all cases

[43] Case studies from the clinical and applied sciences follow this in-depth framework.

except with the researchers. In this interview style, questions were based around a specific guiding framework. There were several instances where a structured interview was used, though this was done only to draw comparisons between specific areas in the case studies (Robson 1993). The interview styles were adapted to the situation reflexively as I, the interviewer responded to the interviewees (Brandell &Varkas in Thyer 2001).

Follow-up interviews were conducted with the four planner respondents in Portland and Toronto. I conducted these to pursue the specifics of green roof projects and related policy-development in those two cities. These interviewees were chosen by reason of their involvement in relevant programs. I also conducted one follow-up with engineering staff in Vancouver to clarify the cost changes in SWM in recent years.

In order to ensure anonymity of the respondents, I do not quote directly from the interview transcripts. I produced an ethical review prior to the study and had those respondents with whom I had in-person interviews sign a release form stating that they understood the study in which they were participating and agreed to take part in it. I also ensured them that they could, at any time and without penalty, withdraw from the interview or refuse to respond to a question. I kept the interview tapes and transcript results of the interviews locked in my office, in a drawer in my personal desk until such time that they will all be destroyed.

During the interviews, I took extensive notes that I used to guide my reporting on the findings from the transcripts. I also took note of some of the main non-verbal communications going on, such as hand gestures (Forester 1999). It is important to note here that the interviews were all taped in their entirety, with the exception of those conducted over the phone. These were for informational purposes only and transcripts were not produced. For the relevance of the information being collected, the informal telephone interview was just as effective at gathering data as the in-person interview.

In situations involving these professionals and the discussion on sustainability, I found it more effective to conduct the interviews in person, as it allows for a more relaxed atmosphere between the interviewer and the respondent. The value to the interview results from this relaxed context is that interviewees are more likely to share personal stories and experiences with you. Though not of critical relevance to this thesis, the anecdotal information is a great entry-point into the larger discussion around sustainability in the respondents' respective practices.

Analytic Framework

The ***Sustainability Framework of Analysis*** listed in the following chapter flowed out of the broader analytic framework, which is summed up in ***System Conditions*** also in the following chapter. The analytic framework that I employed consisted of the eight main factors influencing sustainable SWM development. I decided on this type of framework, as it is supported by the concept of sustainability that I defined in chapter **2.2**. Indeed, the analytic framework and principles of sustainability informed each other as the thesis developed. The principles behind the analytic framework are based in the findings from the case studies, interviews and literature review. The ***System Conditions*** framework is also transferable to any municipality in North America for assessing existing SWM structures and determining areas for change in shifting to more sustainable systems. The same holds true for the ***Sustainability Framework of Analysis*** and the ***Catalogue of Contextual Conditions***, both of which are found in the following chapter.

Biases and Beliefs

As a community planner myself, I have taken part in the discussion with municipal staff and decision-makers around capital allocation. Working in First Nations planning allowed me to see how alternatives are weighed according to capital budgeting. In my work with NGOs, I have witnessed and fed the vast clearinghouse of information available to municipal staff and decision-makers around alternative options to traditional infrastructure and energy planning. This position extends to the insight around the difficulties that decision-makers face in choosing between options, especially those that are not standardized. Of course risk and insurance come into play, but even beyond those considerations, there is a great deal of reticence in municipal planning and politics in moving out of the status quo and onto the "cutting edge", as sustainability planning is so often labeled. These experiences and perspectives kindled my interest in discovering some of the barriers and opportunities to implementing sustainable alternatives. I believe that there are tangible reasons behind the inertia of the status quo. I also believe that cities as the locus for population concentration are headed in an unsustainable direction; that the infrastructure and land use planning and development are counterproductive to moving in a sustainable direction. My work in planning is based around the understanding that time is limited in making the shift to sustainable systems and the research we do at present is critical to informing decision-making in the future that is more fiscally and ecologically-constrained.

For the most part, my SCARP coursework revolved around social and ecological sustainability planning. My bias in planning is explicit; I think that 'sustainability' is not a special interest corner of a planning department, but that it weaves throughout every aspect of municipal functioning, be it social planning, engineering, or youth services. For this reason it was difficult to narrow the scope of areas into which this investigation delved.

My research is also informed by my belief that individuals within a bureaucracy can affect a great deal of change in shifting the path of dependence. Without the ability of the individual with his/her background, experiences and education, organizations and bureaucracies would be entirely entrenched within the unsustainable path. This bias informed a great deal of the thesis research, as I focused on the interviews and how they helped me interpret the ways the vast array of alternative strategies out there are and can be implemented through municipal planning.

I bring my theoretical background into my planning practice to a great extent. Taking lessons from the literature, I have found many ways that they can be enacted through planning. This includes the Thermodynamics theory. Increasingly, I see opportunities to apply this understanding of heat energy in systems at the urban planning level. This bias towards sustainability through the lens of thermodynamic application runs throughout my thesis and is reflected in my planning practice.

There are also other areas of this investigation where I was sure to be upfront with my biases, especially during the interview process. This is not to say that I engaged in a discussion about thermodynamics at each stage of interviewing, but I voiced my sustainability beliefs at the outset of each interview. Indeed, it was often part of the discussion with the respondent before and after the interview.

4.0 Findings

Sustainable Stormwater Management Systems

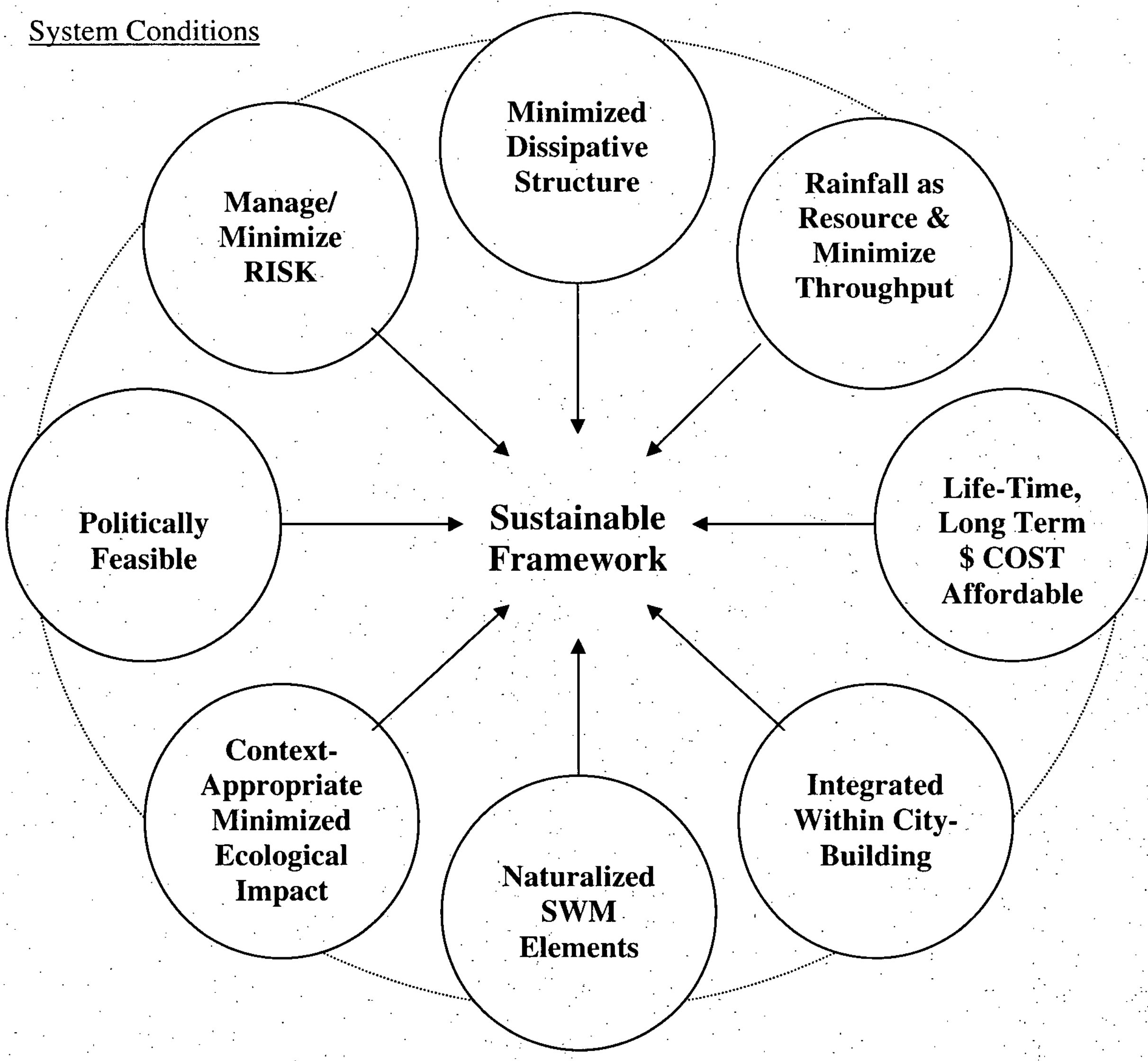
"*Stormwater is the result of how land is developed and managed at every point above where it becomes a problem*" **Rocky Mountain Institute 2004**

Keeping in mind the first research question in this thesis, I offer up here in this Findings chapter the criteria that grew out of the interview responses and the literature review. I develop these over the course of this chapter as categorical guidelines for determining optimal system frameworks and criteria. These criteria are then used to generate specific programming opportunities for sustainable SWM elements. The eight general system conditions create an analytic framework through which SWM system elements are assessed. They are each general categories, but from them flows a sustainability framework of criteria for sustainable SWM features. I argue that if a SWM system fails in any of these categories, it cannot be considered sustainable. There may be aspects or features that are more sustainable in and of themselves, but I am assessing the sustainability of a city's entire SWM system. I go on to provide an answer to the second research question of this thesis in Chapter 5.0 Results and Conclusions. The final question, which poses the challenge of defining the path forward is answered in Chapter 5.1.

By analyzing the problem extensively throughout chapter 2, I developed an understanding of how and why contemporary linear SWM systems function unsustainably. I used the interview responses and literature to build the diagram of necessary system conditions found below. By defining the functional parameters and performance objectives of a sustainable SWM system, I then saw the emergent system condition requirements found below. Though the interviewees were not asked outright about their thoughts on thermodynamics in SWM, I did ask about sustainability in general and then probe further to determine their understanding of how systems' material degrades over time and the cost in energy and dollars to repair and replace.

The majority of the following aspects came from either the literature or the interviews (most planning respondents spoke about all eight of these implicitly or explicitly). All of the engineers spoke at length of mitigating risk and fiscal sustainability. All the planners interviewed mentioned political feasibility in one form or another and a great deal of emphasis was placed on this aspect of viable sustainable SWM options by my second reader. Truly, without political acceptability, sustainable SWM is dead in the water.

<u>System Conditions</u>



- Manage/Minimize Risk

Hydrological modeling and GIS are routinely employed to predict runoff increases from increasing impervious surface area (Yu 1993; Arnold & Gibbons 1996; Shamsi 1996; Hammer & Hammer 2001; Grigg 2003; BC Water Balance Model 2005). Though not ideal, the modeling and computer-aided mapping systems used today should be employed in monitoring changes to runoff rates, increased infiltration, quantity of water taken up in sewer infrastructure and interaction/dynamics between integrated SWM features.

While moving towards more integrated SWM requires less reliance on large-scale infrastructure, this does not mean that there will be more risk of system failure. In fact, integrating and overlapping SWM features increases redundancy in the system, reducing risk of failure. So long as the hydrological monitoring systems continue to provide the same quality of data and SWM features function according to these data parameters, the system will carry less overall risk (France 2002). All interview respondents said that such a system will be more socially, economically and politically sustainable.

- Minimize Dissipative Structure

Highly-ordered physical structures of a system are typically more dissipative in nature than those that are less ordered. Decision-making processes must analyze the SWM alternatives according to their relative tendencies to dissipate materials and energy. When analyzing the differentiated nature of a SWM feature or system, one must take into account the amounts and types of materials and energy that go into its repair, maintenance and construction. When comparing alternatives, the system requiring relatively more frequent repair and material and energy inputs in order to maintain its ordered state is the more differentiated structure (Iyer-Raniga & Treloar 2000). If the two systems perform within the same functional parameters and one is more dissipative[44] (differentiated) in nature, it will be less biophysically sustainable. This component was developed, not through interview responses at all, but solely through the literature. This in itself is an interesting finding; that practitioners do not think to bring this concept into their responses around sustainability of the system.

[44] Of the same input types.

- Rainfall as Resource and Minimize Throughput

If cities' impermeable surfaces are the generators of stormwater, then altering urban surfaces to catch and store rainwater will decrease the amount of stormwater generated. Similarly if rainwater is allowed to infiltrate into groundwater, stormwater throughput creation will decrease. Rainwater is a potential resource in both these examples. While infiltrated rainwater into groundwater is integral to proper hydrological and ecosystem functioning (McHarg 1969; Page 1987; Burton & Pitt 2002), captured rainwater can be used for anthropogenic processes such as small scale urban agriculture (Mallory 1973; Rowney et al 1999), for use onsite in aesthetic features, or in building functioning (Yeang 2004). The more quantitatively and qualitatively effective a SWM system or feature is at performing any[45] of these functions, the more biophysically sustainable it will be.

- Lifetime/Long Term Cost Affordable

Lifetime costing of a system or feature (ideally costs will include an emergy[46] analysis) will produce a metric for comparison with other alternatives. A sustainable SWM system must be economically feasible. The system is more politically sustainable if it is less expensive than alternatives that adhere to the same performance standards. Essentially this comes down to long-term forecasting on cost and revenue increases. If a city is having difficulty financing its infrastructure at present, it will only get worse as costs of repair and construction increase (see section on ***Costs*** in chapter 2.0).

- Integrated Within City-Building

There are numerous ways that SWM features either are or are not well integrated with city-building schemes and processes. A SWM features that is synergistic with a sustainable local transportation plan for instance, will fit into larger planning systems much better than one that stands alone (Moffatt 2001; Moffatt 2004), i.e. a large-volume underground detention pond that heavily disrupts land use or street traffic when repair is needed. Design guidelines that massage SWM features into all aspects of the landscape are a required component of integrated city-building. Combining aesthetic or recreational

[45] A combination of features, each performing one or more tasks will provide complimentary functions.
[46] Emergy is an embodied energy analysis, accounting for energy costs of manufacture/construction, transportation, repair, maintenance and renewal.

features with SWM/rainwater features also serves a learning function, transforming the landscape into a pedagogical tool (Van Der Ryn & Cowan 1996; Rowney et al 1999; Dreiseitl 2004).

- Naturalized SWM Elements

As Kellog (2002), Van Der Ryn (1996), Cowan (1996) and others discuss, cities' built environments perform a (mostly unconscious) teaching function. The natural ecosystems that were once in place prior to city-building must be brought back to light for the city denizens to experience. People's quality of life has been found to be significantly improved when exposed to natural elements such as green plants, trees, streams, forest/ocean views (McHarg 1969; Moffatt 2004). The hard materials and angular constructions of buildings, infrastructure and aesthetic features must be softened to permit the natural world back into the experience of the city. SWM features that are made visible will serve a pedagogical function, as well as increasing aesthetic potential.

Vancouver's storm sewer marking program engages school groups and volunteers in paining a yellow fish in front of neighbourhood stormdrains. This serves to educate people about the ecosystem in which stormwater flows. This would be done more effectively through design of SWM features with streams or other runoff elements. Whenever possible, SWM decision-making should analyze the proposed feature/system in light of this type of sustainably social functioning.

- Context-Appropriate, Minimized Ecological Impact

All respondents agreed that the quality and quantity of pollutant loading in stormwater runoff must be assessed before determining a SWM feature/system. It is crucial to know the amount of water shed off the landscape that goes untreated into receiving water bodies. Many SWM features will either decrease stormwater generation, retain the excess stormwater, or mitigate the stormwater's pollutants. The context will dictate the biophysically-sustainable performance requirements (Kellog 2002; Rowney et al 1999). Mostly, the engineer respondents corroborated the literature in that the analysis of the available alternatives must include the potential to mitigate pollutant loading of receiving ecosystems (IAHS 1977; Grant et al 1996; Rowney et al 1999; Burton & Pitt 2002).

- Politically-Feasible

Because physical, process and functional changes are required in the move to sustainable cities, politically-acceptable solutions are required (Price 2005). Since major social (paradigm) shifts have tended to occur incrementally over time, or through some type of major event (Pierson 2000), rapid change of city structures/functioning is either very slow or extremely rapid. Human civilizations have typically been reactive instead of proactive to gradual (measured in years) environmental changes (Tainter 1988; Wright 2004). This is problematic for the present day politician who wants to shift to sustainable SWM systems that differ from contemporary methods, unless there is a large and obvious monetary benefit with no outright risk attached. All of the planner respondents claimed that because of the need to conserve "political capital", a politician must be able to make SWM decisions in such a way as to be acceptable to the public, without major shocking changes (Price 2005).

Stemming out of the analytic framework above, which is based almost entirely in the direct findings from the literature review and interviews, I have assembled what I believe to be a comprehensive list of sustainable SWM system criteria to be employed in the decision-making and design processes. For ease of analysis, I have grouped these criteria together into the standardized framework in the next section. These criteria will function as a checklist so the planner/designer can assess the relative strengths and shortcomings of the overall management strategy. This is a simple way of determining where the opportunities and constraints lie, as well as where the simplest gains can be made; the "low hanging fruit" of sustainability. There are some instances where I combined the practitioner responses with relevant literature findings to create a new component that I would argue reflects the sustainable SWM requirements most effectively.

SWM Sustainability Comparative Framework of Analysis

"...we are acting and observing from within complex natural-social systems, and these are not amenable to control along the lines of classical paradigms of mechanics, engineering design or even cybernetic regulation".

Funtowicz & O'Connor in Mayumi 1999

I built this assessment tool through review of the literature, interviews, online research and assessment of existing frameworks through the sustainability lens. The framework is fundamentally based in the "discovery of regularities" (Robson 1993, pg. 372) between the interviews and literature review. There are many commonalities that come out of the literature and the experiences of professionals working in this area. By matching the corresponding data from the interviews with information from the literature, plausible outcomes can be determined. This iterative approach is a form of *explanation building* (Robson 1993) that gains validity through matching interview and case study data, in this case comparing municipal practices, with data and information from the literature.

The following checklist (**Figure 5**) is similar in function and style to the one developed by the *American Institute of Certified Planners* (AICP) through the American Planning Association (APA) for guiding sustainable urban development. The AICP checklist, called the Actions for Sustainability Checklist, has become a useful tool for planners in the assessment of planning actions (APA 2003). This *SWM Sustainability Comparative Framework of Analysis* will not provide options in and of itself, but will guide and focus the analysis of system components in order to generate more sustainable options. It is fundamentally a comparative framework for assessing strengths and weaknesses of options. As well, the sustainability framework is used in the assessment of physical SWM structures and not in the policy or plan components, which are integral to a sustainable SWM system.

Figure 5: Sustainable Stormwater Comparative Framework of Analysis

	Criterion	Strength of component in context	Performance Standard E.G.P.	Weakness of component in context
1	Lifetime of the SWM component			
2	$ cost of building the component			
3	$ cost of annual repair/maintenance			
4	$ cost of monitoring for repair and performance			
5	Types of material and energy inputs required for criteria 2, 3 & 4			
6	The level of integration with existing aspects of SWM planning/design		☐ ☐ ☐	
7	Utilization of aesthetic potential		☐ ☐ ☐	
8	Hydrologic appropriateness			
9	Contribution to using rainwater/stormwater as a resource			
10	Ease of future integration into stormwater recycling			
11	Level of component facilitation of smartgrowth and/or urban sustainability (i.e. AICP checklist)		☐ ☐ ☐	
12	Conduciveness to/facilitation of green building integration/design			
13	Goal/Performance-orientation		Appendix III	
14	Appropriateness for the contextual urban natural history (next section)		☐ ☐ ☐	
15	Facilitation of and sensitivity to natural functioning of the ecosystems		☐ ☐ ☐	
16	Replication of natural ecological and/or hydrological systems			
17	Evocation of natural ecological systems, i.e. SWM as pedagogy		☐ ☐ ☐	
18	Relative risk			
19	Existence of feedback loops to allow for adaptive management[47]			
20	Indictors for measurement of success			

Key
E: excellent; G: good; P: poor.

[47] For a discussion on Adaptive Management in SWM, refer to Appendix II.

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1	Lifetime of the SWM component			
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6	The level of integration with existing aspects of SWM planning/design		☐ ☐ ☐	
7	Utilization of aesthetic potential		☐ ☐ ☐	
8	Hydrologic appropriateness			
9	Contribution to using rainwater/stormwater as a resource			
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11	Level of component facilitation of smartgrowth and/or urban sustainability (i.e. AICP checklist)		☐ ☐ ☐	
12	Conduciveness to/facilitation of green building integration/design			
13	Goal/Performance-orientation		Appendix III	
14	Appropriateness for the contextual urban natural history (next section)		☐ ☐ ☐	
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20	Indictors for measurement of success			

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E: excellent; G: good; P: poor.

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The particular physical features of a SWM system to be analyzed in the Sustainability Framework should be chosen based on their appropriateness of fit to the second framework, the *SWM Catalogue of Conditions*.

- The first element in the framework defines the range of years of functionality that can be expected from the system before it must be repaired or replaced. Longer relative lifetimes are more sustainable. Because all elements are not built the same year, the annual rate of deterioration will be unfixed. This allows for dedication of a smaller annual budget for the upgrading/renewing of the system, but it also means that a municipality is beholden to allocating these annual costs in perpetuity (Hammer & Hammer 2001; Grigg 2003).

- The fifth criterion relates to the type and origin of the materials/energy inputs. As noted earlier, a city is a dissipative structure, the maintenance of which requires inputs from outside its boundaries. If the materials and energy are non-renewable and are sourced from great distances, the overall system is relatively insecure and ultimately not sustainable (Rifkin 1989; Iyer-Raniga & Treloar 2000).

- Because one of the initial objectives is to gradually shift existing SWM structures towards more sustainable designs, the practitioner must analyze how the new feature will fit into the functioning of the existing structure. The sixth criterion examines the integration of a new feature into the larger system. This is fundamental to ensuring redundancy and decreased overall risk in the system. If there are multiple structures, especially at the local level, working synergistically, the entire system will perform to a higher standard (Moffatt 2001). This will also assist the interdepartmental integration of SWM planning into a municipality's overall holistic SWM strategy (City of Olympia 2003, Miller 2004).

- Water design features are an aspect of landscaping found scattered throughout North American cities, Vancouver included. These landscape design features are typically constructed strictly for aesthetics, built of concrete and draining water resources instead of being functional. They should decrease impervious surfaces, mitigate stormwater creation and increase available water resources (McHarg 1969, Marsh 1998; Dreiseitl 2003; Moffatt 2005). Criterion seven relates to how well the feature is used to increase the natural beauty of the built landscape, while also performing the previously-mentioned functions.

- The eighth criterion defines how well a SWM feature fits into the local hydrological context, for example, in many instances it is inappropriate to infiltrate rainwater into the ground (France 2002). Because cities have sometimes been built in unsuitable locations such as river deltas, on unstable slopes, floodplains and sensitive ecosystems, it is often inappropriate to increase groundwater levels, introduce contaminants to the soils, or overload the hydrologic regime (Marsh 1998). An example of this is Vancouver's *Roof Leader Disconnection Pilot Project*, whereby a technician performs a site visit to determine if the hydrology of the site is appropriate for infiltration of the stormwater runoff generated by buildings on that site.

- Shifting people's perceptions from rainwater-as-waste to rainwater-as-resource is fundamental to sustainable SWM. The ninth criterion takes into account the importance of having a SWM feature that facilitates the practical use of rainwater. This would include water for use in buildings, flushing toilets, cleaning, cooling, heating (geothermal), etc. (Hamzah & Yeang 2004; CAGBC 2004), as well as outside for recreational or aesthetic water features, irrigation, groundwater recharge, urban agriculture, wetlands, regulating stream flow, etc. (Rowney et al 1999; Dreiseitl 2003; City of Vancouver 2004).

- Recalling that path-dependence entrenches future decision-making, criterion ten assesses whether a SWM feature built into the system now limits future opportunities to move towards an optimal goal such as rainwater recycling. No feature should, by way of design or construction, limit the possibilities for developing future, more sustainable options (Rowney et al 1999).

- The eleventh criterion determines level of integration of the SWM component with *smart growth, the Natural Step*, or *Sustainability Principles of Development.* The goal of this criterion is to integrate SWM with other sustainable city-building tools (Miller 2004).

- As cities move into new development paradigms in the future, green buildings will be front and centre. Because these types of buildings are increasingly being designed to fit into local ecological contexts, criterion twelve focuses on SWM features that should be designed for future integration into green buildings. This includes structural features (Best Management Practices will be discussed in the following chapter) such as rainwater detention ponds, infiltration ponds, swales, constructed wetlands, etc. that can be extended to new areas, be shared by other building drainages, or designed in concert with new buildings (Condon 2004; Hamzah & Yeang 2004).

- By way of design, some SWM features will outperform others at mitigating stormwater, others are focused on dealing with sediment, or contamination. Criterion thirteen assesses how well a feature performs its specific task (see Appendix IV).

- Once an Urban Natural History assessment (Urban Natural History will be discussed later in this chapter) has been performed, criterion fourteen analyzes how well the SWM feature fits into the local historic interplay between the natural and built environments (Kellog 2002).

- The fifteenth criterion assesses how well the SWM component works symbiotically with local ecological functions. This will include climatic, vegetation and riparian concerns. The monitoring of these functions can be done through a *Water Balance Model* (www.waterbalance.ca), integrated GIS, hydrological monitoring/water testing.

- The sixteenth criterion looks at how well the natural systems are being mimicked by the SWM feature. *Biomimmicry* is a concept in *Natural Capitalism* being studied and used in business practices, whereby a system of production mirrors natural ecosystem processes (Lovins 2004). SWM features should adopt, as close as possible, the functioning of the local natural hydrological regime (Page 1987; Dreiseitl 2003).

- The environment in which people live teaches them lessons about the world. Sometimes these lessons are very subtle, others are not, such as filling in wetlands or the canalization of streams and rivers. Criterion seventeen examines how effectively the SWM feature teaches people about the ecosystem and rainwater management functioning of the natural environment. If the inhabitants of a city are not aware of the natural functions of the ecosystem within which that city is built, those people are less likely to understand the importance of minimizing stormwater impacts to that natural system. Public participation in SWM planning and design has been proposed by practitioners of sustainable SWM, who also advocate for a teaching component in the final built feature (McHarg 1969; Rowney at al 1999; France 2002; Dreiseitl 2003).

- No SWM system eliminates risk entirely. The City of Vancouver has different SWM performance standards for different land uses. Even the most ambitious engineering goal for stormwater mitigation is the 25 year storm event (see Graph 1 for rainfall intensities). This is the performance standard for 'trunk' sewers[48], which cover a tributary area greater than 100 acres (City of Vancouver engineering staff 2004). Shifting to an integrated system should reduce risk from its previous level, but it cannot entirely eliminate it. Criterion eighteen assesses how well a SWM feature addresses risk of failure, i.e. overwhelmed mitigation capacity, flooding, property damage. The reality of life in a city is that there is always risk of a natural event beyond the scope of our preparedness. Risk management is understanding and accepting realistic risk.

- A SWM feature should be adaptable to changing conditions and new input from practitioners. Criterion nineteen determines the presence of feedback mechanisms from both a component's performance and planner/designer input. The clearer the feedback

[48] The performance guidelines for residential land use is the 5 year storm. For downtown/commercial and industrial areas it is the 10 year storm.

loops, the more effectively the data will be communicated and built into the SWM system, i.e. through iterative adaptive management.

- The twentieth criterion determines indicators of a feature's success. Recall that performance goals are different for different features, i.e. some mitigate flow, others mitigate pollutants, others deal with sediment. The features work in concert to address all the overall management objectives.

Catalogue of Context Conditions

Figure 6: SWM Catalogue of Conditions

	Natural Element	**Description**	**Data**	**SWM Performance Objective**
1	Annual average amount of rainfall			
2	Annual peak rainfall			
3	Average monthly temperatures			
4	Days of sub-zero °C temperatures			
5	Geological substrate	Limestone ☐ Tells ☐ Sandstone ☐ Shale ☐ Riprap ☐ Hardpan ☐ Silt ☐ ☐ ☐		
6	Presence and type of riparian zones			
	Anthropogenic Element	**Description**	**Data**	**SWM Performance Objective**
1	Roads, sidewalks, parking lots, impermeable surfaces			
2	Presence of contaminants			
3	Land use type			
4	Building types, locations			

Adopted from IAHS 1977; Page 1987; Rowney at al 1999; Burton & Pitt 2002, personal telephone interviews with designers and engineers.

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Adopted from IAHS 1977; Page 1987; Rowney at al 1999; Burton & Pitt 2002, personal telephone interviews with designers and engineers.

Appendix IV offers a list of SWM structural *Best Management Practices* (BMPs) components, though any others that the planner or designer discovers can also be assessed in the following framework. By using the general range of Excellent, Good and Poor, the planner/designer can use the groups to quickly eliminate those features that clearly do not fit.

Natural History Assessment

As well as a revue of the location at present, a temporal assessment should be carried out. An appropriate decision-making process must take into account the historic interplay of the dynamic shaping forces at work between cities/urban areas and the natural world. At certain points in the process of urbanization it is very difficult to discern the contours, drainages and characteristics of the ecosystems[49] that were once in place before humans began shaping the natural environment. As Kellogg (2002) demonstrates, the form of a city is molded by such natural factors as its location, topography, soils, hydrology, climate, geomorphology and sometimes plant and animal life. The natural history of a city can tell incredible, often hidden stories about the forces at work in shaping that location's specific path of development (Kellogg 2002).

Conversely, the history of a city can demonstrate the influences that human development have had on the natural features and systems within which it is built. Fundamentally it is the people and their values and abilities that affect these changes; their perceptions that determine the decisions, designs and plans. There is an interplay between the two shaping forces that results in the present day urban form of a city. A sustainable SWM system should have a natural history study commissioned for the specific locations under consideration.

[49] Also lost are the aesthetics and visual understanding of the pre-existing natural landscape.

Cost Benefit analysis

An integral aspect of decision-making in planning and politics, a cost/benefit analysis of the sustainable SWM features within the entire system would be beneficial to the decision making process. Typically in performing such a measure of analysis as a cost/benefit process, planners have had difficulty in measuring and monetizing many ecological and social costs/benefits. If there is to be a relative measure from which comparisons can be made in a cost/benefit, then it is usually a monetary metric (Lindsay et al 1995).

The cost/benefit analysis would be effective at evaluating the relative benefits of a more sustainable SWM system to the City of Vancouver. A system cannot be considered sustainable if it is not affordable, so those systems that are built for longer relative working lifetimes than those typically built right now in the city will show up in the cost/benefit analysis. This will however, take a lifetime accounting method to embrace the true costs of a system. In new developments, with effective SWM design features, developers have seen decreases in costs of overall construction (Condon & Isaac 2003). The Oregon Museum of Science and Industry (OMSI) development is such a case, whereby the cost savings from construction of sustainable best management practice structures vs. traditional stormwater sewerage facilities lowered the overall development costs significantly, even after high-cost design fees were included (France 2002).

There are, as noted above, many aspects of the cost/benefit that lie outside of the monetary metric. Surprisingly, only five of the interviewees (planners) mentioned externalities in the discussion around cost/benefit. This was of surprise, as it is a widely-discussed factor in most of the recent literature. The values of non-eroded stream beds, maintaining effective groundwater infiltration/proper levels and channels of surficial runoff are all benefits of the cost/benefit equation, yet none carry monetary values in the current market system (Lindsay et al 1995; France 2002). Similarly, the costs of environmental remediation to the receiving water bodies are external to the typical economic framework. These externalities make a thorough evaluation of a SWM system, one that takes into account the value of the ecological framework in which the system is embedded, problematic. An evaluation technique that includes those benefits and costs that are not valued in the typical framework of the cost/benefit should be used. The technique of 'contingent valuation' is one way in which these aspects of decision-making can be valued within the framework of the current market system (Lindsay et al 1995).

Interestingly, City of Vancouver staff commented most frequently and in depth on the external components to a cost/benefit analysis in SWM. With the Crown Street Sustainable Street project designed and built by the City of Vancouver, the concept of sustainable SMW is becoming more common knowledge. At the time of this research, the Crown Street project was just in its initial development stages. Perhaps the high respondent rate amongst City of Vancouver staff was due in part to the relatively high profile of this project.
(http://vancouver.ca/engsvcs/streets/design/images/CrownStreetSummary.pdf)

Wrap-up

Keeping in mind that stormwater is the "physical phase of precipitation" (France 2002, pg. 125) generated by human-built impermeable surfaces[50], the literature and interview responses maintain that management of it can be done either at the source or at the end. Managing the source was described by one respondent as akin to "demand side management" in transportation planning. This is a management approach designed to decrease the load on the system[51] by removing or decreasing the causal agents of stormwater, resulting in decreased requirements for system capacity. One component of this is the rethinking of rainfall,[52] and thus stormwater, as a resource. If, for example, at the building level rainwater was deemed a resource, buildings would be more likely to have some catchment and storage system to make use of the precipitation that fell on it.

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[50] Aside from instances of exposed rock, or desert contexts of flash flooding, stormwater is non-existent in the natural environment.

[51] By decreasing the number of people driving single occupancy vehicles, demand side management reduces the amount of road capacity that must be supplied. The parallel in this case would be decreasing the amount of water that must be dealt with through the current piping system.

[52] Viewing and treating rainfall as a resource, necessarily decreases amounts of stormwater.

There are relative costs and benefits to every possible feature in a system that are dependent on location. All planners, designers and several engineers asserted that the fundamental metric for comparison between SWM options is the suitability of the management component to the specific city's context. The system should also be composed of features allowing it to be dynamic, so it can respond and be easily and cheaply adapted to new circumstances (Iyer-Raniga & Treloar 2000). For example, new conditions such as extreme precipitation events leading to water shortages or flooding, changing demands on water resources through agriculture, overuse, construction of water features, etc.. Because climate has been changing rapidly in recent years, typified globally by unseasonable temperatures and precipitation, and more drastic storm events (Rifkin 1989; Funtowicz & O'Connor in Mayumi & Gowdy 1999; Rees 2003), SWM systems will have to be dynamic enough to respond to increasingly extreme parameters. For instance, the GVRD's most recent climate projections show a 10-30% increase in regional precipitation in the fall and spring seasons over the next 80 years (Connoly 2005).

A sustainable and effective SWM system requires that all of the many components be, not only location-specific, but designed with best fit into the regional watershed. France (2002) demonstrates the importance of watershed planning to sustainability by looking at hydrological carrying capacity of the watershed, i.e. determining the maximum amount of stormwater that can be assimilated by the watershed's water bodies. This would determine the parameters for hydrological modeling and planning of new developments. Since there is no single ultimate human-made answer[53] for managing stormwater, determining which tools are most appropriate for a particular system requires a framework by which decisions can be guided.

[53] There is no single physical structure of anthropogenic origins that will address all of the aspects of a sustainable SWM system. The best system for managing stormwater is that which came about through millennia of structuring from energetic processes in the natural environment.

5.0 Results and Conclusions

Stormwater Management Options for Vancouver

"If the built environment is a powerful silent teacher, we can change the message people get from it. It can be redesigned so that people are richly informed about their place and the ecological processes endemic to it". **Van Der Ryn & Cowan 1996**

The interview responses and literature review lead me to conclude that Vancouver needs to develop an integrated management scheme for stormwater. Integrated management requires an understanding of the interrelationships between:

- land use;
- architecture;
- transportation networks: street layouts and designs, pedestrian/cyclist networks;
- materials in construction/use;
- construction practices;
- open spaces;
- parks;
- riparian areas;
- physical engineering standards.

It appears that planners, designers, decision-makers and engineers in Vancouver most often enter into the discussion through the Ministry of Water, Land and Air Protection's Stormwater Planning: A Guidebook for British Columbia. I argue in this thesis that all planners, designers and engineers need to go much further beyond this. It is crucial that SWM be recognized as an umbrella system, overlapping many other areas of city-building. This concept is not the entirety of sustainable SWM, rather it is the initial principle of learning. Moreover it is the place where we can see the beginnings of changing perception among decision makers. The City of Olympia's SWM guidebook is an encouraging document that takes the discussion a step further in their Draft Storm and Surface Water Plan. In this document are several references to sustainable SWM systems, though it still attempts to work within a flawed framework of low density development. The City of Toronto is implementing "innovative" SWM policies in several of its municipalities (http://www.toronto.ca/water/protecting_quality/stormwater_management/watershed.htm

The City of Toronto is faced with massive costs to repairing one major component of their SWM system. The city has constructed a massive catchment silo, oriented vertically below grade. The energy, materials and dollars spent on this structure annually amount to roughly four million dollars (City of Toronto engineering staff). By most estimates, the maintenance of this structure will continue to increase at 5% annually. No one was prepared to comment on the inevitable dollar costs of replacing this structure.

Integrating SWM into aspects of city-building and management such as lot permeability, environmental site remediation, transportation planning, development approval process, zoning, design guidelines and more is a key aspect in the future sustainable city. I will expand on these concepts in the following sections with Onsite and Offsite Planning.

Onsite-planning

Onsite SWM addresses lot, parcel and building conditions. The factors controlling runoff at the lot level include:

- percentage of impervious surface;
- overall average coefficient of runoff[54];
- soil and geological substrate;
- topography;
- lot size;
- landscaping elements such as vegetation;
- building envelope design;
- constructed-drainage infrastructure.

The examples of Portland and Toronto demonstrate that municipal governments can exercise a great deal of control over these factors through zoning, developer education, density bonusing, design guidelines, development guidelines and alternative building incentives. Through careful planning it is possible to change policy and zoning such that there are higher overall percentages of porous materials covering the ground, greater containment and reuse of rainwater and decreased amounts of stormwater leaving the site.

[54] As determined through the rational method.

The City of Portland established a green investment fund through the Office of Sustainable Development and has allocated funds to green building and green roof projects. The *G-Rated FAR* fund has only been used twice since its inception in 1999, though this small number is related to lack of developer exposure (Miller 2004). Portland also uses a series of educational tools for developers and property owners around stormwater management, with the goal being zero discharge into the Colombia River.

In a contemporary example of following path-dependence, Portland is considering their $1.4 billion *Big Pipe Project* in which city engineers will design a single, giant stormwater pipe to "eliminate" all CSOs and stormwater problems (Portland staff, 2005). Ironic though it may be, Portland will be faced in the future with tragic costs of repair/maintenance and increased risk from reliance on this single pipe. By consolidating the network into one trunk sewer pipe, there is no redundancy in the system. In the event of failure, damage, or needed repair downtime, the entire system is placed at risk, as there are no comparable backups. This is the ultimate offsite solution and carries zero of the benefit generated by the dispersed network of onsite options, in which redundancy is a central component. This option was commented on by several of the City of Portland interviewees. To ensure anonymity, no quotes will be used here, though all of the respondents spoke at length about the many poor elements they saw in this project.

- <u>Onsite Options</u>

Not only is the SWM goal to decrease overall stormwater flow, but the sustainable system would decrease contaminant concentrations in receiving water bodies, lower total amounts of suspended solids and decrease peak discharges off a site (Burton & Pitt 2002). The city of Malmo, Sweden relies on onsite retention of stormwater to decrease CSO activation, risk of flooding and to bolster natural hydrological regimes (Rowney et al 1999). Clearly there are multiple performance objectives and goals of onsite SWM, many of which must be facilitated by policy, bylaws, or guidelines (Rowney 1999; France 2002). Taking feedback from interviewees and combining it with lessons from case studies in the literature, I developed the following standards for Vancouver's sustainable SWM system components. Unless Vancouver relies on costly and unsustainable end of pipe treatment facilities, effective pollutant removal processes and features should be held to certain standards, including:

- Stormwater detention times must be at least 24hrs, depending on infiltration rates;
- Stormwater must not be concentrated in one area, but distributed throughout the network of SWM features;
- Depending on runoff source, minimum annual rainfall of 100 mm (for dilution of pollutants) is required;
- Stormwater (generating) sources to a features should be varied to dilute the more polluted with relatively clean water;
- There should be as many pretreatment features as possible, such as settling and constructed wetlands before stormwater is infiltrated to groundwater;
- Vegetation used to treat stormwater should be highly tolerant of pollutants typically found in that context.

Typically referred to as BMPs by SWM professionals, Best Management Practices are individual aspects of the larger management processes for stormwater, sanitary sewage, groundwater preservation, drinking water and other utilities provision. BMPs include policy, design, process and structural elements. Structural BMPs are design elements that address the most appropriate physical elements of the landscape that need to be incorporated into the development of a site. BMPs are "schedules of activities, prohibitions of practices, maintenance procedures, managerial practices, or structural features that prevent or reduce adverse impacts to waters" (City of Olympia 2003). Each SWM objective should be matched up with the onsite structural BMPs that are designed to address the desired task. Options for Vancouver include:

- Site impermeable surface allowances zoning;
- Roof leader/drainage connection to infiltration beds;
- Roof leader disconnection from stormwater infrastructure;
- Stream daylighting and riparian conservation;
- Coordination programs between landowners/developers for education about SWM;
- Onsite structural BMPs;
- Retention ponds/basins;
- Cisterns;
- Constructed wetlands;
- Infiltration beds, berms, swales;
- Green roofs.

Offsite-planning

All the aspects of the urban fabric surrounding a site comprise the offsite aspect of SWM. This area of SWM is extensive and typical considerations are cross-departmental and include:

- Connectivity from site to offsite SWM infrastructure;
- Type of SWM system, i.e. CSO, straight to treatment plant, swale, curbless gutters, ditches, gravity-fed straight pipe to receiving water body, etc.;
- Situation/location within the watershed;
- Transportation infrastructure, i.e. road and street characteristics;
- Land uses (residential, commercial, trunk);
- Runoff types and constituent pollutants from different land use types;
- Densities;
- Structural urban design elements such as sidewalks;
- Characteristics of surrounding land uses, such as type of surface coverage, percentage of surrounding impervious surfaces, proximity to water courses such as stream, rivers, lakes, oceans (beaches) and other drainages;
- Permeable paving systems;
- Swales, infiltration beds, berms, non-structural BMPs such as riparian protection policies.

A key objective of offsite SWM is increasing the overall infiltration potential of city surfaces. Permeable paving technologies have been around for decades and are currently being tested out in various locations around the world (Rowney et al, 1999; Booth & Leavitt, 1999). The most effective method of reducing impermeable surfaces in urban areas is to reduce the overall amount of pavement dedicated to road networks. This works in concert with *Smart Growth* policies, *New Urbanism* principles and the *Natural Step* framework. Very simply, Vancouver has over 36 km^2 of roads, lanes and sidewalks, almost all of which are impermeable. If these areas could be addressed through integrated transportation and SWM planning, Vancouver would see drastic improvements in SWM, but also in walkability, bike transportation corridors, transit, air quality, dense/complete neighbourhoods/communities and proactive planning for peak oil.

- Offsite Options

The goal with the offsite SWM scheme is to mitigate the peak discharges, deal with increased overall flows from individual sites into the system and contamination of the stormwater entering receiving water bodies. The multiple ways of addressing these objectives include offsite non-structural and structural BMPs (Rowney 1999; France 2002; GVRD 1999). They are most commonly employed for stormwater retention, but often also work to increase the overall amount of permeable surface. They work most effectively at retaining stormwater in order to alleviate the load on peak stormwater discharge, though they should also be employed to decrease contaminant loading and overall stormwater flows (Page 1987; Rowney 1999). Designing with an integration of these features requires a rethinking of urban aesthetics. Because these options can depart from the linear, hard-edges that we are so accustomed to in cities (France 2002, Dreiseitl 2003) they tend to "soften" the urban landscape.

Urban Stormwater BMPs

It is typically much easier to design BMPs into new developments, as BMPs can sometimes be poorly suited for redesign into existing urban areas. This is especially true of those sites in Vancouver that are already well established. Structural and non structural BMPs are very well suited to addressing greenfield[55] site development. Indeed it is always easier to address a problem from the beginning, instead of after a behaviour is entrenched or a city built (Pierson 2000).

BMPs can be grouped into categories of a) managing the volume and discharge times of stormwater flows; b) managing pollution sources; c) managing the treatment of stormwater runoff quality (GVRD 1999; City of Olympia 2003).

Types of offsite structural BMPs[56]:

- Minimized Connected Impervious Areas (MDCIA);
- Coalescing Plate Separator/Interceptor (CPS/CPI);
- Extended detention basin;
- Retention pond;
- Wetland basin;

[55] "Greenfield" development refers to those projects taking place in rural, or non-urban areas that have no pre-existing structures on them.
[56] See appendix B for table on uses, applicability, and appropriateness of each of the BMP options.

- Porous pavements;
- Infiltration basin;
- Wetland channel;
- Media filter;
- Grass swale (typically roadside);
- Grass buffer strip, grass filter strip (typically roadside);
- Percolation trench;
- Swirl-type concentrator;
- Dry well;
- Water quality inlet.

Industrial Ecology

The SWM system for the City of Vancouver should be designed in such as way as to provide benefit to other, complementary systems, i.e. transportation, aesthetic. The larger systems' functioning of the city would be made more effective and efficient. In working towards a larger, holistic management plan for dealing with the stormwater that falls on Vancouver as a resource instead of as a waste to be removed as quickly as possible, an industrial ecology framework should be applied in the decision making process.

Designing SWM features to take advantage of rainfall, instead of just simply shunting it off the (typically impervious) urban surfaces, would provide cost savings in the provision of those services. Here in Vancouver, we experienced record drought in the summer of 2003 and 2004, yet the city receives an annual rainfall of close to 1,300 mm. The SWM plans for the city should be taking this into account. For example, by using stormwater in buildings to flush toilets, run heating/cooling systems, or cleaning. There would be significant cost savings in many departments (Pratt in Rowney at al 1999).

SWM is moreover, dealt with in isolation. That is the system of stormwater management is looked at in and of itself in planning, engineering, and design[57]. As we lean on technical engineering as the only solutions for our urban issues, our systems of management grow in complexity. Systems' complexity also means more extensive

[57] Looking at stormwater management is a growing theme among progressive urban designers and landscape architects.

bureaucracies are required to maintain them, as well as higher associated costs and diminishing returns (Tainter 1995). In place of technical, linear and one-dimensional engineering, we need is a systems science that takes into account social and ecosystemic realities.

Opportunities

The British Columbia *Local Government Act* places the responsibility of SWM squarely on the shoulders of municipalities (MWLAP 2002). The tools and impetus are there for Vancouver to move forward on this, yet implementing SWM options for the city requires dedication from the leadership, planners, engineers, and designers. The *Local Government Act* dictates that municipalities must produce a *Liquid Waste Management Plan* (LWMP), of which a SWM plan is a required component. The LWMP is developed through public participation and green roofs have been brought up by the public on a regular basis in this (Theaker 2004; Mickelson 2005). The present political, social and development climates in Vancouver present an opportunity to implement sustainable principles of design and planning. Though a more in-depth analysis is needed, the "red hot" building and construction industries right now, especially in market housing, affords greater leeway in municipal dealings with developers. There is opportunity to leverage sustainable policy concepts into market housing and developments for both the above stated reason and the shifting demands of Vancouverites.

I would argue that a sustainable SWM system absolutely requires that a maximum stormwater discharge bylaw be implemented. Many European examples such as Malmo (Sweden), Stuttgart (Germany) have zero stormwater discharge bylaws, whereby any stormwater coming offsite into the SWM network is charged a fee (Rowney et al 1999; Von Hausen 2005). Combining this with alternative development incentives, developer/ public education and cost-sharing measures provides a solid system for shifting the decision-making, development and planning milieus to be more amenable to sustainable SWM.

Roofs generate a great deal of stormwater flows in a city. Greening of the rooftops is a viable aspect of SWM in Vancouver. By this I refer to a living system placed on top of either a pre-existing or new structural roof (see next chapter for full discussion of green roofs). A green roof is related to the design of a building envelope and I have grouped it into onsite options, as its performance is very much related to SWM goals. Compared to many other options, a green roof can be a relatively low-cost and attractive component for controlling the source of stormwater.

The benefits of the green roof option are felt beyond just SWM, making them an optimal design feature. Long accepted in Europe, green roofs provide multiple benefits and are part of the future of sustainable SWM in North America. Germany already has an extensive green roof program and a related multi-million dollar industry (Pedersen 2000). Related benefits include: reduction of the urban heat island effect, decreased ground-level airborne pollutants, increased green space and community garden opportunities, building insulation, decreased summertime building cooling costs and shifts in the perceptions of urban dwellers away from the strictly "rational"[58] city towards a more natural aesthetic. I will pursue the implementation of green roofs in Vancouver further in the next chapter.

Constraints

The main issue in sustainable SWM planning does not seem to be whether or not the technology, designs, or best practices exist, but rather the social, development and political determinants of the system. These play the largest role in determining SWM design and planning and include: political will, practitioner knowledge of/exposure to SWM alternatives, capital allocation priorities, perception/acceptability by the public, local ownership of the process, localized design, planning milieu and developer cost/benefit sharing and above all the impetus behind decision-making (Condon 2004; Kamstra 2004; Miller 2004; Theaker 2004).

[58] Highly linear, hard edged, non-organic, engineered.

As discussed earlier, we have elevated rationality[59], through technical engineering, above all other bases of decision-making in our city-building (Friedmann 1973, Friedmann 1987, Sandercock 1998). At any time in modern history, the rational comprehensive model of planning has been based on the paradigm-driven (path-dependent) understanding of a problem at that particular time. Because the Newtonian paradigm of scientific reductionist thinking has been the dominant worldview throughout contemporary planning, it has become the ultimate arbiter of our decision-making in much of municipal SWM. This has become a major constraint to planning and building sustainable SWM systems.

One could also say that in urban SWM lies the embodiment of rational hubris. Our streets are perfectly engineered for traffic flows at high speeds to accommodate specific sized vehicles of different uses and to shed the stormwater equivalent of the rainwater that falls during a twenty-five year storm (for large catchment basins and trunk sewers). This further entrenches the institutions of engineering standards, acting as positive feedback and taking us further down the path dependence model. The path becomes cemented in place and so to do our cities. (Pierson 2000). A simple illustration of this is found by picking up a stormwater infrastructure guidebook such as Hammer and Hammer (2001) or Grigg (2003). The positive feedback loops in the path of dependence also reinforce other land uses that take advantage of the output of the linear model, including road paving, car oriented development, loss of green space for parking lots. As mentioned in the Peak Oil chapter, there will soon be a reckoning of how the related infrastructures of stormwater, transportation, trunk water and utilities are delivered and constructed in Vancouver and all cities.

A prominent and highly-revered designer once told me - and I paraphrase here - that it would take a monumental, paradigmatic shift to even begin to address the sustainability of SWM in Vancouver. At heart, that's what this thesis aims to address. The investigation into this dilemma turned up an encouraging aspect of the surface water

[59] This is often referred to as the sphere of the 'technical planners', who have guided the hand of the rational comprehensive model of planning.

management strategy for the City of Olympia. In the plan, the Public Works Department staff included a statement about how addressing the issue of SWM will require a re-envisioning of solutions, previously viewed as "radical". According to their strategy, "the best way to manage urbanization impacts on surface waters is to eliminate them before they occur. This is difficult for new developments, and requires radical thinking for existing ones. But, if protecting water resources is important and to be successful, it will take a perception change-that which is not radical must become mainstream" (City of Olympia 2003, City of Olympia staff 2004). This statement is very much in line with what this thesis has been arguing for: a perception/paradigm shift and the accompanying design, plan and engineering changes.

From a sustainability standpoint, planning and building a system now that binds future generations to dealing with an annual cost of replacement or repair that the municipality may or may not be able to afford is an unsustainable plan. Steps that can be taken now, lowering the costs of expansion, upkeep, and repairs to the SWM system will result in a more sustainable system.

Though politically difficult, decision making in the present that is weighted more heavily on benefits to the future is the mark of sustainability. The often narrow timeframe of political office tends to shorten the horizon of considerations for decision making, leaving future problems to future politicians. Greider in Pierson 2001 (pg. 261) recounts that in 1981, David Stockman, who was the budget director for the Reagan administration in the US, when "asked by an advisor...to address Social Security's severe long-term financing problems, Stockman dismissed the idea out of hand. He explained that he had little interest in wasting 'a lot of political capital on some other guy's problem in [the year] 2010'".

5.1 Green Roof Implementation Strategy: A Framework

"We do not seek to imitate nature, but rather to find the principles she uses".

Buckminster Fuller in Oberlander et al 2002.

Fleshing out a sustainable SWM system in Vancouver requires the application of policy, bylaw, planning guidelines, design innovation and education of the public, decision-makers, designers and architects. Because they must integrate with existing city-building processes and plans, implementation strategies specific to Vancouver for each SWM technique, feature or component are required. As an example of such an implementation strategy, green roofs are one of several effective starting points in shifting perceptions and addressing larger problems of sustainability. Green roofs are a key aspect in integrating "water with site and architectural design" (France 2002, pg. 126), which should be the paradigm that guides onsite SWM and design in general. I intend to use the following ***Green Roof Implementation Strategy*** as an example of the key elements that should be contained in such implementation frameworks. This strategy acts as a model for implementing other elements of sustainable SWM in Vancouver.

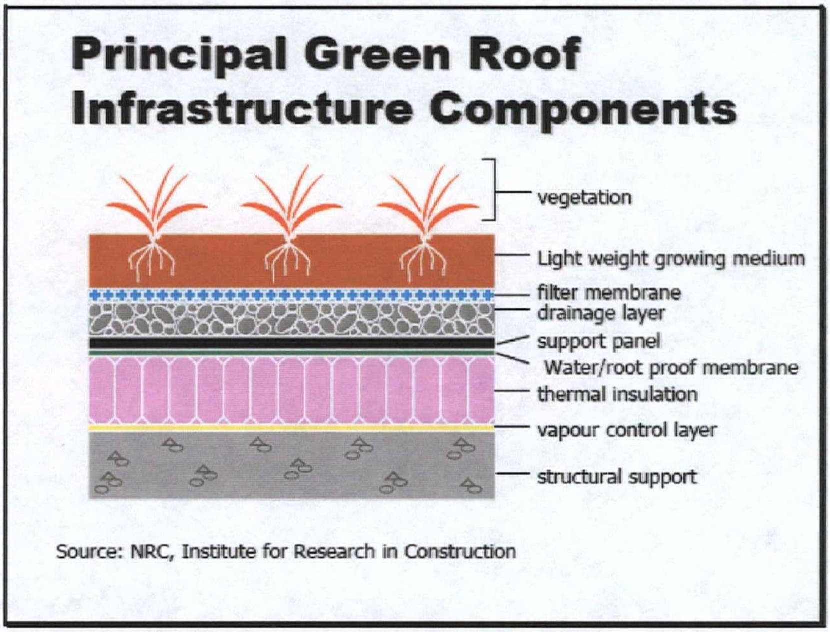
The following sections of this chapter outline a strategy, in the form of a *Staff Report to Council*[60] for implementing green roofs on a city-wide level. This chapter provides a detailed background on green roofs, discusses researched benefits to them and provides data on costs, benefits and obstacles. There is discussion about the best practices learned from other Canadian and US municipal case studies, as well as relevant global examples. Green roof retrofitting and new buildings' strategies for intensive and extensive green roofs, costs, considerations and aspects of construction are also discussed.

[60] I follow this format, as it is used for policy recommendations to council for consideration and approval.

Green Roofs

A green roof is several layers of organic and non-organic material placed on a water and root-proof membrane on an existing roof, either below, at, or above grade. We determine a green roof to be either extensive or intensive, depending on the depth of the growing medium and sometimes the intended uses and planting types.

Figure 7: Components of Green Roofs



Components

- Plants (low, hardy alpine and dryland species[61]);
- Growing media[62];
- Landscape or filter cloth (for roots & growing medium, allows water runoff);
- Drainage Layer (gravel, polystyrene and may be formed with reservoirs);
- Root repellant membrane (inert chemical or metallic lining).

From Petersen 2001

In the Vancouver context of development there are few incentives to the building developer to incorporate sustainable SWM features into a site. In the following chapter, I outline a strategy for implementing the green roof component of onsite SWM in Vancouver. A key consideration of this implementation plan is addressing the developer incentives and disincentives for SWM and building-performance through design and construction of green roofs.

[61] Depending on: climate and growing media depth and roof loading capacity.

[62] Usually lightweight, mineral based: either sand, gravel, crushed brick, pumice, organic matter and soil.

Without (dis)incentive, the added cost of a green roof would not usually be made part of a developer's pro forma[63]. There is little $ impetus in the marketplace right now for a developer to incorporate sustainable SWM or other features into their projects. Pending data from an important green roof study underway in Vancouver at present[64], the benefits of green roofs are arguably experienced more offsite than they are in the building, i.e. stormwater reduction, improved air quality and environmental aesthetics vs. increased 'R' rating, better cooling in summer, availability of rainwater for building use, increased roof lifespan and increased green space for building occupants.

Typical Benefits:

- Increasing the amount of space occupied by photosynthesizing plants by 1.5 m2 can remove up to .3 kg/year of particulate matter from the air;
- Dramatic decreased peak stormwater flows during growing season;
- Dramatic decreased overall flow of water offsite during growing season;
- Filtration of airborne particulate and contaminants;
- Increased evapotranspiration from photosynthetic plantings, leading to onsite and offsite cooling;
- Local environmental cooling and decreased urban "heat island" effect from reduced albedo, leading to a decrease in volatile organic compounds (VOCs);
- Regulation of building heat exchange through roof (research on the quantifiable energy exchange benefits of green roofs is ongoing in Vancouver[65], the data from which will be available before the end of 2005);
- Improved quality of stormwater runoff in general;
- Community food-growing and amenity park space;
- Aesthetic improvement in views;
- Habitat for birds and pollinating insects;
- Acoustical benefits;
- Improved experience of natural elements in the city;
- Greatly increased roof lifespan through protection from heating/cooling, UV.

Sources: Beckman et al 1997; Paloma Del Barrio 1998; Pedersen 2000; Niachou et al 2001; Oberlander et al 2002; Peck & Khun 2003; Ecoroofs Everywhere 2004; Mutton 2004; Connoly 2004 & 2005; GRHC 2005.

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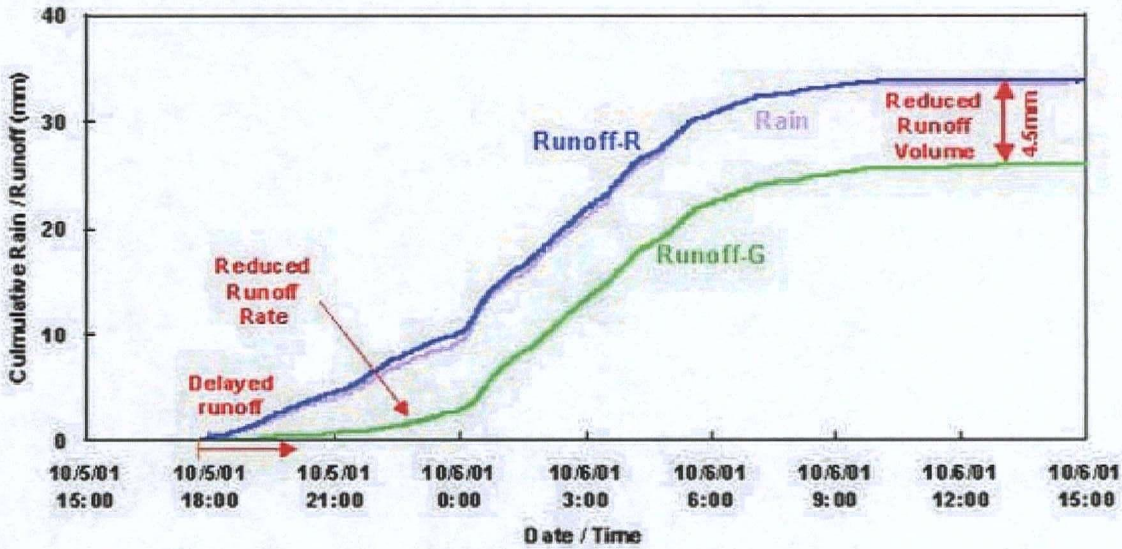
[63] The cost and profit accounting analysis for a future project.

[64] BCIT's Great Northern Way Campus green roof research facility, headed by Maureen Connelly.

[65] BCIT green roof research station.

Figure 8 shows a comparison between the flow of stormwater off a green roof and a "reference", or 'control' roof. Runoff-R is stormwater from the reference roof and Runoff-G is from the green roof. The graph shows a 15 hour period of time, during which 34 mm of rain fell on the two roof structures in Ottawa Ontario in October, 2001. The 4.5mm "Reduced Runoff Volume" is rainfall depth equivalent of flow off the roofs.

Figure 8: Green Roof and Reference Roof Stormwater Flow Comparison



Source: NRC's Institute for Research in Construction.

Green roofs have been an accepted aspect of European development now for many years and are just beginning to catch on in North America. The cities of Atlanta, Portland, and Seattle in the US have installed green roofs on their city halls and counties in Maryland and Vermont have built green roofs on some of their county buildings (American city and County, February 2004). Toronto Ontario has a demonstration green roof on its city hall.

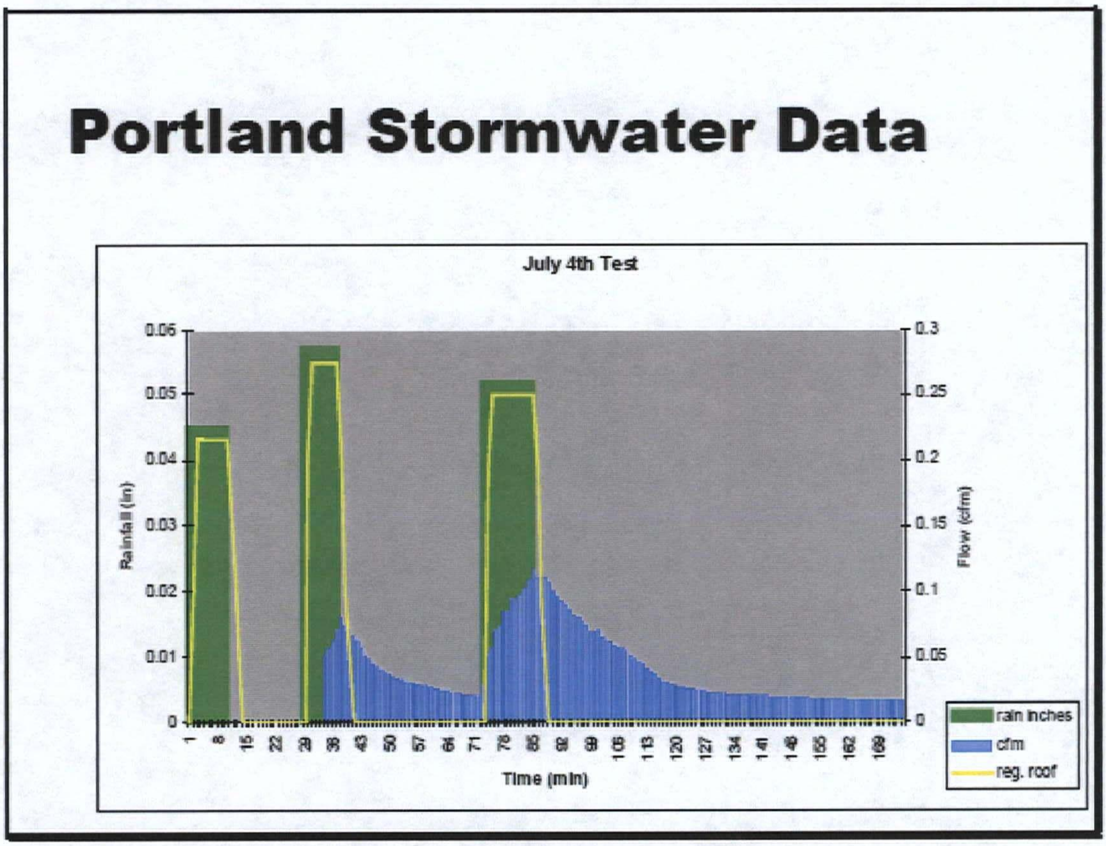
Increasing numbers of Canadians are turning to "green design" in their homes (CAGBC 2004; Theaker 2004). More analysis is needed, but the shift in consumer preference towards green buildings, energy efficiency standards and sustainable design should be

- The depth and properties of the materials regulate the temperature such that the roof itself will experience reduced fluctuations in temperature;
- The plant layer will keep wind off roofs, decreasing heat flux;
- The substrate and well-established plants add an insulation value up to R20.

Adapted from Oberlander et al 2002; Peck & Khun 2003

Green roofs alone carry no single outstanding benefit, but the emergent property of the green roof is far more advantageous than the sum of its parts. Of course, the greatest benefit is the reduction in peak and overall stormwater flows off site (**Figures 8 & 9**).

Figure 9: Peak Discharge Differences; Regular and Green Roof



Adopted from Pederson 2000.

A green roof will trap and store rainwater that will either be returned to the local environment through infiltration, evapotranspiration/evaporation, or will be released to municipal stormwater sewers slowly over the course of days instead of minutes, the rate of which will be partially dependent on the depth of the roof's soil and the time of year/productivity of the vegetation. This will decrease the need for large diameter stormwater pipes. Portland's *Office of Sustainable Development* is quantifying more precise numbers of green roof-depth to pipe-diameter equivalents in response to the proposed "Big Pipe" project (Miller 2004).

Portland Oregon, experiencing similar climatic conditions as Vancouver, found similar stormwater mitigation results in **Figure 9**. These data and those from **Figure 8** clearly show the reduction of both overall flow and peak runoff from the green roof. These outcomes are seasonally-dependent. Due to the high rates of rainfall and low rates of evaporation during Vancouver's winter months there would not be an average reduction of overall flows to the extent of 55% shown in **Figure 9**.

Context of Green Roofs in Vancouver

Emerging from the Canadian Government's ratification of the Kyoto Accord is Vancouver's "Cool Vancouver" initiative, led by a task force for both corporate and community initiatives. Green roofs will improve air quality, decrease ambient air temperatures (urban heat island), lower collective roof albedo and remove airborne particulate that adds to the reflectivity and trapping of heat within the Earth's atmosphere (Pedersen 2000; Oberlander et al 2002; Peck & Khun 2003; Connelly 2004).

The sustainability goals of the 2010 Olympics will be partially met by initiatives such as the green buildings and progressive design guidelines in Southeast False Creek, as well as the green buildings' and green roofs' strategies for the rest of the city. Since they can be highly visible, green roofs offer high profile aesthetic value for sparking interest, generating dialogue and incrementally shifting perceptions.

The City of Vancouver has a Green Building Policy of LEED rated Gold for all institutional buildings over 100,000 ft^2. Green Roofs can earn a building up to 8 LEED points towards the Gold rating requirements of 39 points (CAGBC 2004).

Attributes

Attributes of ***Extensive*** green roofs:

- relatively shallow soil horizon/planting medium;
- typical substrates from 8-20 cm;
- limited plant types, i.e. grasses, mosses, sedums;
- controls stormwater runoff through retention, filtration, evaporation, and evapotransipration;
- relatively low maintenance requirements/costs;
- relatively low structural loading, with fully-saturated weights[71] ranging from 115-300 kg/m^2;
- can be pre-cast from plastic molds;
- can be designed for and built on roofs with up to 45 degree slopes;
- not typically meant to have human traffic;
- relatively low-cost addition to existing or typical roof.

Attributes of **Intensive** green roofs:

- deeper soil and planting horizons[72] from 20-120 cm;
- plant types can range from sedums, to shrubs, to food-growing plants, to small trees;
- usually designed by landscape architects;
- potentially high roof-loading potential, with fully saturated weights[73] ranging from 125-2,000 kg/m^2;
- often requiring structural retrofit or initial structural design of building;
- won't sustain as great a slope as extensive green roofs;
- greater expense to builder/developer;
- can sustain human traffic;
- high maintenance requirements;
- greater benefits to direct and indirect users, i.e. people in contact with the roof, the local users of the environment, anyone who breathes air, or uses water.

Recent GVRD Directions

The GVRD has developed their *Buildsmart* program, which includes green roofs, green buildings and green design. Their list of components of building green includes energy and water use efficiencies, building orientation, materials choice and sourcing, design process and SWM.

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[71] Roughly 23-60 lbs/ft^2.
[72] Up to 48 inches.
[73] Roughly 25-400 lbs/ft^2.

Vancouver's Experience With Green Roofs

There are many green roofs in the city, some that have been around long enough to demonstrate the effectiveness of the technology. The more high profile examples include UBC's downtown Robson Square campus, which is an on-grade intensive green roof that provides valuable green space to the downtown area. The roof of the Downtown Vancouver Public Library, designed by Moshie Safdie has an extensive green roof that some of the custodial staff say has significantly reduced runoff since its construction (Pedersen 2000). Arthur Erickson's Waterfall building has a 150,000 ft^2 extensive green roof that has received accolades from the design community and consumers alike[74].

Construction

A green roof sits on top of an existing structure. There is a water/root-proof membrane situated between the green roof and the structural roof itself. Though there is some added weight to the structure, many buildings do not have to be altered because of the presence of the green roof. Many buildings can be retrofitted with an extensive green roof with no structural modifications (Peck &Khun 2003; Connoly 2004). Intensive green roofs usually require a structural upgrade, but this again depends on the existing building's materials and design (Wexler 2004). This does not preclude the construction or redesign of drainage elements on the roof that bring the stormwater runoff into the building itself for use in several applications, or for piping into the ground for infiltration (Yeang 2004).

Structural engineers divide loads into two categories: dead loads and live loads. The dead load refers to the weight of the roof structure itself and any permanent functional elements. The live load includes elements such as human occupants, snow, rain, maintenance equipment and other transient items. Structural considerations must be made for both the weight and dimensions of equipment and materials that may be used at various stages of construction and maintenance of the roof (Wexler 2004).

If the green roof is designed into a building from the outset, the structural considerations can be made with little or no cost whatsoever, depending on the type of green roof. The

[74] See also Canada Harbour place, Waterfront Hotel herb garden.

costs with developing new buildings with green roofs are accrued through the necessity of "special design considerations" (Wexler 2005) and materials and labour associated with the green roof only. These costs will be dependent on factors such as: extensive or intensive green roof, depth of planting medium, type of pre-cast mold, plant types, design fees, maintenance requirements and irrigation systems (urban agriculture in the summer).

In many cases, green roofs may be installed on existing buildings with no structural retrofit or changes. Anytime a green roof is added to an existing building, a structural engineer must assess the potential loading and determine the specifics of the design and construction. Vancouver's building codes have determined the load-bearing characteristics of existing roofs in the city. Sometime there is little allowance for the added weight of a fully saturated green roof, though for extensive green roofs this is not the case (Wexler 2005). Intensive green roofs however, can carry structural retrofit costs that are considerable.

There are many instances where the existing materials on the roof can be removed to allow for the weight of the green roof instead. Take, for example, concrete roofing tiles, which have a dead load of roughly 70 kg/m^2 (14 lbs/foot^2). Another example of gravel roofs shows a dead load of approximately 20-100 kg/m^2 (4-20 lbs/foot^2), depending on gravel depths (1-5 cm respectively). In these cases, removing the existing load and installing a low-weight extensive green roof would not require any structural enhancement (Peck & Khun 2003; Connoly 2004) and could decrease net weight.

The roofing membrane guarantee issued by the Roofing Contractors Association of British Columbia (RCABC) does not preclude the installation of green roofs. So long as the membrane's manufacturer guarantees its work, which most now do, and the building owner accepts responsibility for the associated costs of removing the green roof in the event of a membrane failure, the RCABC will guarantee the roof.

A roof with little or no slope (<5 degrees) requires some type of assisted drainage system to ensure that the roof does not retain water in puddles sitting on the waterproof membrane (Connoly 2004). A sloped roof greater than 10 degrees requires special construction techniques and features in order to ensure against slipping. Typically this would include installing a raised grid, horizontal slats, or some anchoring technique.

When a green roof is designed for a building, the civil/mechanical engineer will determine the flow rates and volumes of runoff in order to size the piping that will drain the overflow from the roof into the storm sewer or ideally, infiltrate into the ground (Wexler 2004). Because of this necessary consideration, it is impossible to produce a normative statement on runoff pipe and/or drainage requirements for green roofs.

There is a worksheet in LEEDs that has the flow and perviousness characteristics of different site and roof surfaces. This sheet is used to determine the net effect of various areas for green roofs, though this information will be made regionally-specific only after the results of the BCIT study are published.

Costs

Costs of installing green roofs vary greatly, depending on numerous factors. Chiefly among these considerations is the structural aspect. This requires a building-by-building approach to retrofitting, as each structure will be specific in both its existing load-bearing capacity and the design of the green roof itself (Oberlander et al 2002; Wexler 2004).

Though the green roof market is changing continuously and there are many different products available, the costs of the pre-cast green roofs vary from \$7-\$25 ft^2 (Soprema 2004). This cost reflects a typical extensive system and does not take into account specifically-designed intensive green roofs. In these latter roofs, high costs can be accrued through the fees of landscape designers (CMHC 2004). Extensive green roofs will add no more than 30% onto the costs of the roof. These costs are the up-front development costs and reflect only the bottom line and not the triple bottom line, the lifetime costs of the roof, nor the operating costs of the building. If the potential energy savings from the insulation and longer lifespan for the roof are taken into account, the annual cost over the lifetime of a green roof may only be half that of a conventional assembly (Peck & Khun 2003).

A conventional roof costing $100,000 with a lifetime of 24 years, depreciates at $4,200 annually. A similar extensive green roof would cost up $135,000 and last about 36 years, providing an energy savings of up to $70,000. The annual depreciation of this roof would be about $1,800. These figures do not reflect any potential repair costs that may result from improper installation or maintenance.

Current Challenges and Considerations

a) regulatory: The City of Vancouver requires that developers must get all buildings insured against potential leaks. Since the "leaky condo crisis", developers and insurers have been loathe to take on new projects where there is the slightest chance that the building might leak. Addressing these concerns can be done at several levels.

In the rezoning costs to a developer, roughly 50 cents per square foot goes to municipal sewerage costs. Green buildings and green roofs can see distinct decreases in sewerage requirements of the building, i.e. decreased water use in the building and lower amounts of stormwater runoff off the building into SWM infrastructure from the green roof. As stated earlier, overflow from the green roof would ideally be infiltrated either into the ground, cisterns, retention ponds/beds, or constructed wetlands (site permitting for all). These overflow options would be relied on predominantly during the winter months, but are necessary requirements nonetheless.

It is more difficult to implement a regulatory regime on smaller and lower density residential housing structures than it is on commercial, civic, mixed-use, or industrial buildings, as per square foot costs go up as building FSR goes down. Higher density residential structures, on the other hand, offer no such issues, as relative costs go down as FSR goes up.

b) non-regulatory: The development industries in Canada and BC are not educated in the fields of green roof design and construction, insurance, maintenance, costs, benefits and product availability. There are currently few firms offering knowledgeable green roof services in Vancouver, resulting in relatively higher costs for design and construction.

In retrofitting buildings for green roofs, there are structural issues that need to be researched. Since very little has been done on this in Vancouver, there is no formulaic way of determining structural changes that are necessary for green roof retrofitting. This is a hindrance to the process of project assessment. An intensive green roof with a horizon of 10 inches can weigh roughly 70 lbs/foot^2 when fully saturated. Over the whole, say, 10,000 feet^2 of a green roof, that can amount to 700,000 fully saturated pounds. As stated earlier, typical roofing materials such as concrete tiles or gravel carry associated weights that can be eliminated and exchanged for the green roof, thus lowering the net weight gain of adding the green roof.

Within the context of the LEED system, green roofs garner relatively few points towards certification of a building[75]. The cost benefit tradeoff to the developer going for LEED certification is balanced towards the cost side at present. This is changing as the CAGBC overhauls their regionally-specific LEED point system.

Clearly the biggest challenge associated with green roofs is coming up with ways to overcome the costs. Because the benefits of a green roof are spread between energy savings in building operation, stormwater mitigation, community acceptance and enjoyment, air quality improvement and local environmental heat reduction, it is difficult to monetize them and pass the value back to a developer. Using a contingent valuation method would place a monetary value on these benefits (Lindsay et al 1995), which could then be part of the negotiations over Development Cost Charges (DCCs) and community amenity packages.

[75] Credits 6.1 & 6.2 under 'Sustainable Sites' and credits 1.1, 1.2, 2, 3.1, 3.2 under water efficiency & 7.2 under stormwater.

Likewise with the costs, as it is difficult to quantify the costs of a lack of green space in a heavily urbanized area, or the costs of the extra reflected shortwave radiation off typical high-albedo roofs, or to agglomerate the costs (listed earlier in **Chapters 1 & 2**) directly related to roof runoff. Again, the contingent valuation method could be used to quantify and monetize these costs (Lindsay et al 1995), which should be included in the development permit application, zoning variance application and proforma.

The overarching challenge to private and public sectors' widespread implementation of green roofs is the general lack of understand and knowledge about green roofs. There is a lot of misplaced skepticism over the integrity/ability of the green roof systems at preventing leaks, damage to roof/building, associated costs, etc.. This most often comes down to an issue of liability, but is also just a problem with perceptions.

Since a green roof is typically installed on top of a conventional roof, it will protect that roof from the sun, freezing, thawing, wind, thermal exchanges, etc.. Though a properly installed and maintained green roof may have a lifespan longer than even that of many contemporary buildings (Oberlander et al 2002), there are several ways that the roof could possibly fail.

The most common concern in ensuring the integrity of the green roof is its installation. There are strict guidelines to be followed for what types of materials can be used in the installation, what types of footwear the installers can wear and the disposal of refuse. A green roof will keep the roof wet for long periods of time. If the installation is flawed in any way, the result will be serious leaking and require immediate maintenance (Oberlander et al 2002; Peck & Khun 2003).

Recommended City Directions and Actions

Recommended research directions are as follows:

- Affordability, i.e. lack of market availability of products in and around Vancouver[76];
- Structural issues;
- Envelope issues such as leaking caused by poor installation, design guidelines, etc.;
- Benefits to the developer, such as cost/benefit sharing;
- Determine which manufacturers could very simply retool their processes to manufacture the green roofing materials;
- Context of the LEED system, i.e. there should be more emphasis on the green roof as SWM feature in assessing LEED points?

Currently a major development in Vancouver carries a DCC of $9/ft^2. Of that nine dollars, 30% goes to municipal infrastructure charges. Of that $3, 20% goes to stormwater infrastructure costs (Mickelson 2004). That 60 cents/ft^2 could be partially returned to the developer for decreasing the load on the stormwater infrastructure through a combination of green roof, below-grade cistern, detention pond, building use of stormwater, or infiltration pond/trench.

In addressing the two aspects of the liability issue, the City must use the research that has already been conducted to demonstrate best practices of construction and design and address the lack of familiarity with green roofs within the development industry. Again, in Germany, there are examples of green roofs that have been in operation for over 17 years, with no maintenance or repair[77].

The development, architecture and design communities must be educated before widespread acceptance will begin to take place. In accordance with this, the supply market should be expanded through education to manufacturers of similar products. There must be clarification and education to all parties involved about the liability and

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[76] There are no suppliers in BC of the pre-form molds required for the extensive green roof system. There are industrial sites on Vancouver Island that have the capacity to begin injecting plastic molds to produce the prefab materials, but who aren't doing so at present.

[77] See the Portland, Oregon publication entitled Green City; City of Portland's Green Building Program Quarterly Newsletter for a discussion on this case study.

insurance issues. Clearing up misconceptions about these issues will shift green roofs into the mainstream of accepted building and design practices.

Changing zoning bylaws to include a stormwater runoff allowance is the crucial disincentive for implementing green roofs at the commercial, industrial and residential scales. By instituting a maximum stormwater runoff volume, beyond which the property owner is charged a fee, the onus for SWM is shifted to onsite management. This would shift the responsibility away from the municipality and ensure that innovation take place during construction of new facilities. These bylaw changes should be grandfathered in over time to allow for site owners/managers time to implement incremental changes.

All new institutional and governmental buildings/sites should meet a zero stormwater discharge requirement, meaning no stormwater leaves a site. The bylaw for commercial and residential buildings should be developed in dialogue with developers and architects, but should include a very low maximum allowable discharge.

6.0 Concluding Remarks

After assessing the inherent limitations of SWM systems that rely on continuous and growing energy and materials inputs, it has become clear that the sustainable city must come to grips with the increasing scarcity of the non-renewable energy and materials upon which it is dependent. As many as possible of the systems of a sustainable city's functions must be shifted to new parameters, intensities and sources of materials and energy requirements.

Regarding municipal SWM, it turns out that biophysical and economic sustainability are very closely linked to one another. A sustainable system of SWM is comprised of low energy features, which decrease both short and long-term costs. At the same time as being more affordable, the sustainable system of SWM decreases impacts to local ecosystems and bolsters natural environmental functions such as hydrological regimes. Developing local production ability and skills around sustainable SWM alternatives adds redundancy to local economies and creates impetus for further research and development. Decreasing a city's reliance on foreign energy and materials lowers risk of disrupted flows of inputs, while also ensuring a more secure local economy.

Sustainable allocation of scarce resources to SWM requires rethinking the system parameters, priorities and objectives. Simply, a city should not sink money into bottomless pits of unsustainable infrastructure, especially not in light of better-functioning and cheaper alternatives.

Vancouver can begin to incrementally shift the ways that stormwater is viewed in the city. Rainwater should be utilized as a resource to bolster local ecosystem integrity, lower demands on regional water provision, decrease amounts of urban runoff to water bodies, be used in buildings' functions, make the city more aesthetically enjoyable and teach people the value of local ecosystems. The Local Government Act gives Vancouver impetus to develop an integrated SWM system. The development market and public opinion in the city have made fertile ground for shifting to "greener", more sustainable solutions. Vancouver's surrounding water bodies require restoration and conservation, both of which can be partially accomplished through sustainable SWM.

As one component of an integrated network of features, green roofs offer the possibility for Vancouver to initiate the shift to sustainable development in SWM. The benefits from green roofs are numerous and extend to multiple user groups who would otherwise not be involved in or aware of SWM issues. Green roofs offer a teaching opportunity and entry point for people into the discussion about urban sustainability through SWM. The multiple benefits from green roofs offer an opportunity to reposition SWM as not merely a process to get rid of surface water, but a way to use the rain that falls on Vancouver to the advantage of local ecosystems, our experience of the city, better design and to our pocketbooks.

As we move into the end of globally cheap oil and gas, the infrastructure that we lay today makes future generations beholden to increasing costs and diminishing returns. Below-street networks of large-scale stormwater pipes entrench the path of dependence in our current paradigm of city-building, especially the car-orientation. There is no point in building today what we cannot afford to pay for in the future, both ecologically and economically. The social aspect is crucial as well. Conventional SWM entrenches the belief for city denizens that our linear and 'highly organized' methods of city-building are above and beyond the constraints of the natural world. That we have separated ourselves from reliance on natural processes through technically-engineered substitutions for complex natural systems is a fallacy, but one that we have been able to maintain for some time, though are not able to sustain indefinitely.

Instead of seeing constraints from SWM issues, this is an opportunity to rethink and redevelop our cities in simply better ways. Sustainability brings with it increases in quality of life, especially through better SWM methods and solutions.

Appendices

Appendix I Coefficients of Runoff and Flow Rate Calculation

Flow is calculated through the following equation: $q=CiA$

q = peak runoff rate in cubic metres per second
C = the runoff coefficient
i = rainfall intensity in cm/hour for specific design storm frequency
A = the catchment area in m^2

Soil Texture	Coefficient of Runoff
Concrete or Asphalt	1
Gravel-Compact	0.7
Clay-Bare	0.75
Clay-Light Vegetation	0.6
Clay-Dense Vegetation	0.5
Gravel-Bare	0.65
Gravel-Light Vegetation	0.5
Gravel-Dense Vegetation	0.4
Loam-Bare	0.6
Loam-Light Vegetation	0.45
Loam-Dense Vegetation	0.35
Sand-Bare	0.5
Sand-Light Vegetation	0.4
Sand-Dense Vegetation	0.3
Grass Area	0.35

Appendix II Elements of Adaptive Management

The following is a list of traits and components of surface water adaptive management, as compiled by the City of Olympia, Public Works Department (Appendix C: *Summary of Adaptive Management Techniques*)

- Is an ongoing process for continually improving management policies and practices by learning from the outcomes of program activities;
- Treats those policies and practices as experiments, and improves surface water management by learning from the ecosystems being affected.
- Relies on scientific methods to evaluate how well regulatory and non-regulatory actions achieve their objectives;
- Links best available science, community values, staff experience, and measured outcomes;
- Recognizes and allows for the uncertainty and incomplete knowledge that typify complex ecosystem dynamics;
- Results in timely and appropriate management decisions affecting the Utility's flood prevention, water quality maintenance, and aquatic habitat protection responsibilities;

The principal components of an adaptive management approach are (modified from Nyberg and Taylor, 1995, and Institute for Agriculture and Trade Policy website, 2002):

- Establishing a responsible entity committed to managing the ecosystem. The Utility is the entity responsible for managing Olympia surface waters;
- Assessing (modeling) the ecosystem, identifying possible management actions, desired outcomes, and information gaps or uncertainties. The Utility assesses what is needed to prevent flooding, maintain water quality, and protect aquatic habitat;
- Assembling one or more management plans and monitoring programs that maximize results, optimize measuring and learning, and incorporate best available science. These plans and programs are built around the Utility's eight Core Services;
- Selecting and implementing the best plans and programs based on its cost, risks, likely outcomes, performance measurability, and other factors;
- Monitoring the key response indicators, thereby measuring performance;
- Evaluating outcomes versus what was expected, and identifying reasons for any differences;
- Communicating results to managers and stakeholders and receiving feedback;
- Adjusting the management plans and monitoring programs to reflect what was learned.

Appendix III Interview Protocol

Question #1
What is your role in the planning, design, development, or engineering of the stormwater management for the city of _______?

Question #2
What are the elements of your SWM plan, i.e. design guidelines, BMPs, planning principles, engineering constraints, development approval processes?

Question #3
Are there aspects of sustainability principles in the plan? Are they stated explicitly or are they implicit?

Question #4
Are there discussions about sustainability, i.e. what it means and how it applies in general and to your municipality?

Question #5
What strategies do you find are most efficient and effective at improving developer to city-staff relations in the realm of stormwater management? Do you have any set strategies in place to address this area?

Question #6
What groups have been included in the implementation of the stormwater strategy? Has it been beneficial to include NGOs in the development of a knowledge bank on sustainable SWM? What about at the building envelope and functioning levels?

Question #7
What has been the easiest to implement of all of the aspects of the stormwater management strategy? Do you think that is transferable to other districts and municipalities?

Question #8
How has the development community responded to the stormwater policy? Has it been easy to address their concerns and if so how has it been done?

Question #9
Do you find green buildings/green roofs to be effective at addressing the issues of sustainable stormwater management? Are these structures transferable across regions, or are they site specific to your municipality?

Question #10
Do you include green buildings as an integrated aspect of the SWM plan?

Question #11
Does this plan include provision for green roofs as an aspect of it?

Question #12
Has your strategy managed the implementation of the green roofs?

Question #13
What does the strategy look like and would it be possible for me to get a copy of it, if it is publicly-accessible? How else would I access it?

Question #14
How has your strategy dealt with issues such as development cost levies, benefit-sharing, cost-sharing, developer-incentives, strata corporations?

Question #15
Has the plan addressed the concerns of developers around development proformas? Has there been a drop or rise in construction of new buildings related to the implementation of this or other sustainability/green plans?

Question #16
In what direction do you see the future of SWM planning and design in your municipality going? Is it headed in a sustainability-based direction, or is it going to stay fairly stable in the direction it is now headed? What do you think, if anything, will affect the direction that future planning will take?

Appendix IV Assessment of Potential Effectiveness of Structural BMPs

Structural BMP Type	Capital Costs*	Maintenance Costs*	Water Quality	Flow Rate Control	Runoff Volume Reduction	O&M Needs	Sensitivity to Site Conditions	Failure Potential	Applicability: Low to Medium Residential	Applicability: High Density Residential	Applicability: High density Commercial	Potential for Thermal Increases	Potential for Groundwater Contamination
MDCIA	-1	-1	4	5	5	-3	1	-2	5	4	1	-1	-2
Extended Retention Basin	-3	-3	4	5	1	-2	3	-2	4	4	3	-2	-2
Retention Pond	-4	-3	5	5	1	-2	3	-1	4	4	3	-4	-2
Wetland Basin	-2	-1	5	5	2	-3	1	-1	4	5	2	-3	-2
Porous Pavement (A, B, D)	-5	-5	3/4/4	5/5/3	1/4/4	-4/-4/-5	3/0/1	-2/-4/-5	1/4/3	5/5/3	5/5/3	-3/-2/-3	-1/-5/-5
Infiltration Basin	-3	-2	4	5	5	-4	1	-4	5	5	2	-1	-4
Constructed Wetland	-5	-4	5	3	2	-3	4	-1	4	4	2	-2	-2
Media Filter	-4	-4	4	1	0	-5	4	-3	1	3	5	-2	-1
Grass Swale	-4	-3	2	3	1	-4	3	-2	5	3	1	-1	-2
Grass Buffer Strip (C)	-1	-1	2	2	2	-3	3	-2	5	3	1	-1	-2
Percolation Trench	-2	-2	4	4	4	-5	1	-5	2	3	4	-1	-5
Swirl-type Concentrator	-2	-4	3	0	0	-5	4	-2	1	2	4	-1	-1
Dry Well/Basin	-5	-1	4	4	4	-5	2	-5	2	3	4	-1	-5
Extensive Green Roof	-2	-1	3	1-3	1-4	-2	5	-4	3	5	5	2	-3
Intensive Green Roof	-4	-3	5	1-4	1-5	-5	5	-4	1	5	5	3	-4
CPS/CPI	-1	-5	5	0	0	-3	5	3	5	5	5	0	-5
Water Quality Inlet	-1	-1	1	0	0	-5	4	-3	1	2	3	-1	-1

Adapted from Urbonas in Rowney et al., 1999; GVRD 2002.

Legend
A: Porous Pavement; Modular with underdrain
B: Porous Pavement; Modular with Infiltration
C: or Grass Filter Strip
D: Porous Pavement; Monolithic
0 to 5: Positive aspects' ranking, where 5 is the most positive;
-1 to –5: Negative aspects' ranking, where –5 is the most negative.
* costs are relative to each BMP.

Appendix V Timeline of Sustainable Development

- 1962-Silent Spring is published by Rachel Carson. Includes work on toxicology, Ecology and epidemiology in relation to pesticides accumulation in the environment to "catastrophic levels";
- 1968-Population Bomb published by Paul Ehrlich. Connecting human population expansion with resource exploitation;
- 1969/70-Partners in Development/IDRC. Considering a new approach to development with specific interest in impacts on Third World countries;
- 1971-Founex Report from the Swiss. Calls for the need to integrate environmental issues into development;
- 1971-Only One Earth written by Dubos and Ward. *Common Future* objectives in the face of increasing global deterioration;
- 1972-Limits to Growth published by the Club of Rome. Predicts the consequences of projected world population growth;
- 1974-CFC report from Roland and Molina. Links CFC production with ozone depletion;
- 1974-Latin American World Model. Third World response to the Limits to Growth. Stressing the need for greater equity;
- 1978-OECD Directorate of the Environment. Linking economy and environment.
- 1979-IIED report Banking in the Biosphere. Exploring reform;
- 1980-Jimmy carter authorizes report in Biodiversity and international development studies;
- 1980-IUCN releases World Conservation Strategy. Redressing inequity, fighting poverty;
- 1980-Brandt Report, North-South, A programme for Survival. Reassessing development;
- 1982-Un Charter for Nature. Links human survival on natural, ecological systems. Espouses the need to curb human exploitation of these resources;
- 1987-Brundtland Report: Our Common Future. Report on WCED popularizes 'Sustainable Development;
- 1992-Changing Course published by the World Business Council for Sustainable Development. Links business interests with Sustainable Development;
- 1992-Earth Summit. UNCED in Rio e Janeiro. Agreements on Agenda 21, Convention on Biological Diversity, Framework convention on Climate Change, Rio declaration;
- 1993-UN Commission on Sustainable Development follow-up to Rio;

- 1993-World Conference on Human Rights. Reaffirming governmental commitments to all Human Rights;
- 1994-NAFTA. Including North American Agreement on Environmental Cooperation, establishes the Commission for Environmental Cooperation (CEC);
- 1995-World Summit for Social Development. International community vows to eradicate poverty;
- 1996-Summit of the Americas on Sustainable Development in Santa Cruz Bolivia;
- 1997-UN General Assembly special session. Little progress has been made towards implementing Agenda 21. Produces a programme for further implementation;
- 1997-Signing of Kyoto Protocol. Delegates to the UN Framework Convention on Climate Change 3rd Convention of the Parties (COP-3) sign Kyoto. Developed Nations commit to reducing several greenhouse gases by at least 5% below 1990 levels between 2008 and 2012;
- 2004-Vancouver adopts the Cool Vancouver Task Force to develop community and corporate action plans for reaching Kyoto targets.

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