Urban watershed health and resilience, evaluated through land use history and eco-hydrology in Swan Lake watershed (Saanich, B.C.)

by

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Bachelor of Science, Royal Roads University, 2004

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Abstract

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Swan Lake watershed, a sub-catchment of the salmonid bearing Colquitz Creek watershed located in the municipality of Saanich, on southern Vancouver Island, British Columbia, Canada, was studied to characterise the linkages between urbanisation and ecological health and resilience. Although rarely applied in watershed ecology, resilience (the ability to absorb disturbances without the loss of ecosystem identity) offers a useful construct in this case study to understand the effects of urban development over the past 150 years, and to outline some principles for integrated, watershed-scale management.

Baseline landscape characteristics and processes of historical land-use were determined using paleoecology (pollen analysis) and historical records. Watershed health was assessed using: a Proper Functioning Condition assessment of riparian-wetland and stream channels; vegetation community mapping; vegetation plots; surface flow hydrology; and water quality analyses. Vegetation and lake hydrographs were compared with less disturbed reference ecosystems. Findings are discussed in terms of alternative stable state models and energy dissipation at the site and landscape scale.

Analysis of the data revealed that over the past 150 years, forest clearing, agriculture, transportation infrastructure, and non-point source pollution have transformed the landscape and substantially altered the water and energy balance. Impervious surfaces and cleared land (covering 25% and 35% of the watershed, respectively) are inferred to

have reduced latent heat dissipation of solar energy, an important landscape-scale process affecting resilience to climate change. Degraded stream channels represent reduced ecosystem services and lost social/economic value. The stream/lake hydrographs revealed a typical, urban flashy profile that exacerbates channel erosion and non-point source pollution, while excessive lake stage drawdown is also evident. Water quality is characterized by historic and ongoing excessive nutrient loading and associated cultural eutrophication, heavy metal pollution, and ecosystem "ageing" due to dissolved solids runoff. At the site level, invasive species, particularly reed canarygrass, dominate Swan Lake wetlands, whereas the pollen record shows abundant woody shrubs and associated species (some of which are now extirpated from the site) and an absence of grass; this helps to establish a rationale for vegetation management.

Based on the findings of the above studies and according to a proposed conceptual model with assessment criteria in five categories (water, vegetation, energy, soil and nutrients), Swan Lake watershed has impaired ecological health and is not resilient to disturbances such as extreme climate/weather events. Future watershed management should therefore mimic the hydrological function and energy balance of the pre-development conditions.

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Acknowledgments

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Chapter 1. Introduction

1.1. Urban Ecology in a Global Context

Ecosystem degradation is prevalent throughout the world, due in large part to the direct and indirect effects of cities. Social and economic well-being ultimately depend on many "services" performed by ecosystems, such as regulation of the climate, provision of fresh water, food, materials and medicine, absorption of wastes, and recreation (Hassan *et al.*, 2005). However, the process of urbanisation is usually carried out with little regard for preserving this life support system. In practically all cities, urbanisation follows a similar pattern (Table 1.1). Native terrestrial ecosystems are systematically cleared and replaced with human-made infrastructure; streams, wetlands and floodplains are channelized, enclosed in pipes, drained and dyked, as water is efficiently conveyed off the land. This results in a high percentage of impervious surfaces, simplified vegetation, and large-scale soil disturbance. Surface runoff increases, washing soil, nutrients and pollutants into local waterbodies, leading to eutrophication (algae blooms associated with depleted oxygen), stream channel erosion, habitat loss and toxic effects on aquatic plants and animals. Furthermore, the loss of water and native vegetation, coupled with an increase in heat sources, leads to the "urban heat island" effect, whereby urban areas are several degrees or more hotter than rural or undeveloped areas (Akbari *et al.*, 2001; Grimm *et al.*, 2008). This leads to worsened air pollution and can amplify natural climate events such as the fatal heat wave in Europe in 2003 (Daihnut *et al.,* 2004).

As shown in Table 1.1, many of the effects of urbanisation are interlinked and feed back upon one another. These effects are well studied (e.g. Alberti, 2005; Marselak *et al.*, 2006; Paul and Meyer, 2001; Pickett *et al.* 2001), yet there are few substantial or integrated initiatives to address urban-related ecosystem degradation (McGranahan and Marcotullio, 2005; Miltner *et al.*, 2004). Furthermore, the influence of cities extends well beyond their borders, in a sprawling "ecological footprint" that is often hundreds of times the area of a city itself (Pickett *et al.*, 2001; Alberti, 2005), thereby contributing to global scale problems. Cities are responsible for 78% of worldwide anthropogenic carbon emissions, one of the main drivers of climate change, along with land cover change associated with urban development (Grimm *et al.*, 2008; Pielke and Niyogi, 2008; IPCC, 2007). More frequent extreme weather events and increased average temperatures, predicted effects of climate change, in turn threaten the well being of urban residents, especially because of urban ecosystem degradation (Bates *et al.*, 2008). While ecosystem services can help to buffer these effects, over 60% of those services reviewed in the Millennium Ecosystem Assessment were found to be degraded or are being used unsustainably (Hassan *et al.*, 2005). Other global-scale studies demonstrate a "great acceleration" in indicators of ecosystem degradation, particularly since the second World War, and show the scale of human enterprise now constitutes a geophysical force (e.g. Steffen *et al.,* 2007). This global context highlights the importance of understanding the interactions between human and ecological systems.

Urban ecology is a relatively new discipline that has emerged out of recognition of these problems, and consists of a variety of approaches to understanding the interrelationships between people and ecosystems (Pickett *et al.*, 2001). However, the complexity of social-ecological systems challenges standard scientific methods of inquiry, calling for new perspectives that integrate disciplines and spatial/time scales (Liu *et al.*, 2007). An alternative to current unsustainable urban development involves considering the cyclical systems of nature, and the potential for humans to have a place and beneficial role within these systems. The concepts of ecological health and resilience provide a framework for beginning this process.

Table 1.1. Some effects of urbanisation*, and linkages between effects

#	Effects of urbanisation	Linked with (#)
1	Increase in impervious areas (pavement, buildings)	1, 2, 3, 4, 5, 9, 12, 17
2	Loss (clearing) of native vegetation	5, 10, 14, 16
3	Loss (drainage) of floodplains and wetlands	4, 5, 16
4	Conveyance of “stormwater” in pipes, discharge to surface water	5, 9, 11, 12, 14, 15, 17, 22
5	Disruption of water cycle: increase in surface runoff, decrease in interflow, infiltration and evapotranspiration	1, 2, 3, 4, 8, 10
6	Air pollution (industry, vehicles)	17, 19
7	Increased potable water use	13
8	(Ground and surface) water pollution – point source (e.g. sewage, industry)	17
9	(Ground and surface) water pollution – non-point source (e.g. runoff from agricultural, residential areas, roads)	11, 12, 17
10	Soil disturbance and erosion	2, 11
11	Nutrient over-enrichment of fresh and marine water bodies	2, 3, 4, 8, 9
12	Dissolved oxygen depletion and algae blooms (eutrophication)	11
13	Water shortages	3, 4, 5, 7
14	Stream channel erosion, incision	1, 2, 3, 4, 5
15	Habitat degradation and/or fragmentation	1, 2, 3, 4, 5, 6, 10
16	Increased air temperature (reduced cooling capacity)	1, 2, 3, 4, 5, 6
17	Toxic effects on aquatic/terrestrial species	4, 6, 8, 9
18	Species loss (extirpation)	2, 6, 8, 9, 11, 12, 14
19	Degraded human health (e.g. respiratory illness, heat-related deaths, cancer)	6, 8, 13, 17
20	Reduced biodiversity	2, 12, 15, 17, 18
21	Soil fertility degradation	1, 2, 6, 10
22	Depleted recreation and amenity value; property value loss	8, 9, 10, 11, 12

sources: Alberti, 2005; Marselak et al., 2006; Paul and Meyer, 2001; Pickett et al. 2001

1.2. Study Area

1.2.1. Overview and Thesis Hypothesis

Swan Lake watershed is located in the municipality of Saanich, within Greater Victoria, situated at the southern tip of Vancouver Island, British Columbia. At first glance, there is little evidence of any problem here: a picturesque lake is protected within the Swan Lake Christmas Hill Nature Sanctuary, while the surrounding areas provide homes, agriculture, transportation and commercial areas typical of a small North American city. However, this ordinariness masks ecological degradation, for example, the lake is subject to frequent algae blooms, stream channels are visibly in poor condition, and non-point-source pollution as well as occasional toxic spills occur (T. Morrison, pers. comm.; P. Lucey, pers. comm.). The illusion lies in the limited perspective in space and time. Connections with other parts of the watershed that affect ecosystem processes are not readily apparent, and without knowledge about the landscape history it is not possible to appreciate what has changed. To date, most studies of Swan Lake have focused on the lake itself or nearby ecosystems, without addressing connections with larger scale influences in both space and time. Therefore, Swan Lake watershed represents an opportunity to examine processes of urbanisation that cross these scales, with a case study to evaluate urban ecological health and resilience. This evaluation can in turn help to identify opportunities for improving impaired ecological health in a human-dominated landscape. This watershed is ideal for this case study for a few reasons: it contains a nature sanctuary that is highly valued for habitat, recreation and education, and that provides access for research; it consists of a variety of land uses, including dense commercial areas, residential neighbourhoods and agricultural land; and it is located close to the University of Victoria and other educational institutions, creating an opportunity for long-term research.

The general thesis hypothesis is: ***Urban development and land use patterns in Swan Lake watershed have degraded ecosystem health and resilience over the past 150 years, as evaluated through history, hydrology and vegetation studies.***

As a corollary to this statement, it is further proposed that ecological health and resilience can be supported and/or restored by emulating the pre-development landscape function.[1]

1 The latter is not a strictly testable hypothesis in the context of this study, rather a proposition.

1.2.2. General Landscape Characteristics

The geology in Swan Lake watershed and the Victoria region in general consists largely of low-relief metamorphic *gneiss* outcroppings that were uplifted when two smaller terranes collided with the land mass forming Vancouver Island and coastal British Columbia (Yorath and Nasmith, 1995). The study area was covered in ice during the Fraser Glaciation, ca. 29,000 to 13,000 years ago; as the ice sheets melted, sea levels rose and flooded low-lying areas and as the weight of glacial ice was relieved, the land mass later rebounded, leaving behind a thick deposit of fine marine-derived clay in local areas below around 60m above sea level, i.e. most of Swan Lake watershed (Yorath and Nasmith, 1995). On top of the clay various organic horizons have formed, depending on local site conditions.

The study area lies within the Coastal Douglas-fir biogeoclimatic zone (moist maritime sub-zone), characterised by warm, dry summers and mild, wet winters (Nuszdorfer *et al.*, 1991). Precipitation in this zone is significantly less than in the nearby and much larger Coastal Western Hemlock zone, due to the rainshadow effect of the Olympic and Vancouver Island mountain ranges (BC Ministry of Environment, no date). At the Victoria International Airport, located 21 km to the north, average annual precipitation is 883 mm, average temperature is 9.7ºC, monthly average temperature remains above zero, and average monthly precipitation ranges from a low of 19 mm in July to a maximum of 151 mm in December (Environment Canada, 2008). Most precipitation is received between October and April.

In representative ecosystems, Douglas-fir (*Pseudotsuga menziesii*) dominates the tree layer of vegetation; other common tree species include western redcedar (*Thuja plicata*), grand fir (*Abies grandis*), red alder (*Alnus rubra*), arbutus (*Arbutus menziesii*) and Garry oak (*Quercus garryana*); less common tree species include shore pine (*Pinus contorta* var. *contorta*), bigleaf maple (*Acer macrophyllum*) and black cottonwood (*Populus balsamifera* ssp. *trichocarpa*) (Nuzsdorfer *et al.*, 1991). Due to the unique climatic conditions of the region, many species are at the northern limits of their range.[2] This, combined with intensive development pressure, has resulted in half the inventoried plant communities in this biogeoclimatic zone being considered rare or provincially endangered (BC Ministry of Environment, no date). In the Greater Victoria area and Swan Lake watershed, Garry oak ecosystems were historically an important ecosystem component, among a mosaic of closed-canopy coniferous forests, open savanna and woodland (Fuchs, 2001). As of 1997, only 0.05% remained of historical Garry oak ecosystems that were present in the Capital Regional District ca. 1800 (Garry Oak Ecosystems Recovery Team, 2007a). A variety of wetland types are common in the CDF zone and are exceptionally valuable ecosystems for wildlife habitat and hydrologic watershed function (McKenzie and Moran, 1994).

Swan Lake watershed is a sub-catchment of Colquitz Creek watershed, a 46 km^2 area that drains to Colquitz Creek, a 3rd order salmonid-bearing stream containing coho salmon, chum salmon and cutthroat trout (BC MoE FISS, no date; Buchanan *et al.*, 2008). Colquitz Creek in turn discharges into Portage Inlet, a marine bay connected to Victoria Harbour by a narrow tidal channel known as the Gorge (Capital Regional District, no date).

Swan Lake watershed is 11.8 km^2 in size (Figure 1.1). Land use in the watershed is a mixture of agriculture, residential housing and commercial centres, and includes a highway and several arterial roads; most areas of original contiguous native vegetation have been cleared.

The majority of the watershed (about 60%) is characterised by soils that have well-drained and dark coloured A horizons ranging from about 5 to 45 cm in thickness, overlying B horizons consisting of clay (and clay loam) or gravelly sandy loam, and a C horizon consisting of marine clay or glacial till; smaller areas are composed of surficial

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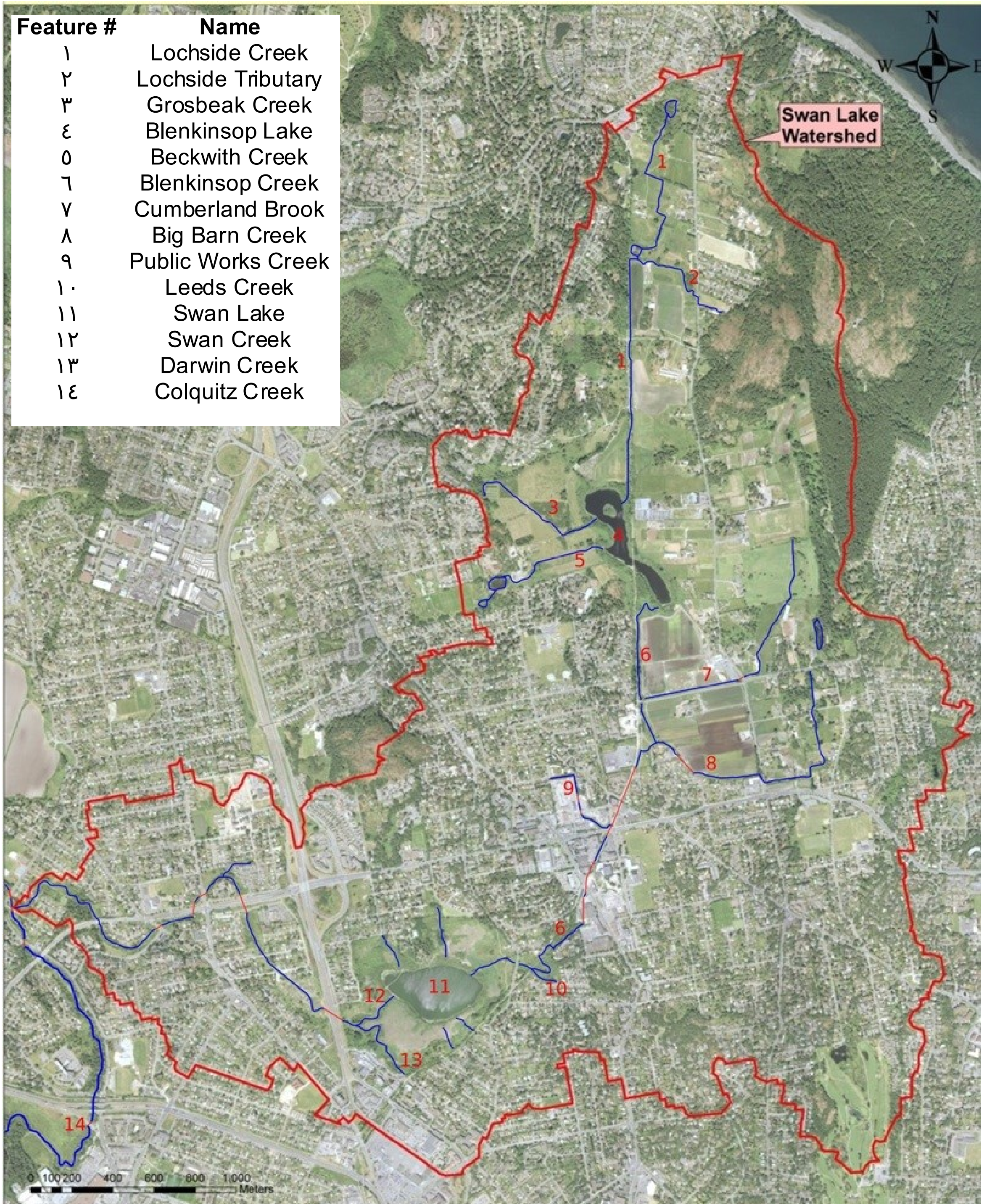
2 For example: phantom orchid (*Cephalanthera austiniae*) (Klinkenberg, no date); white meconella (*Meconalla oregana*), deltoid balsamroot (*Balsamorhiza deltoidea*), coastal chocolate-tips (*Lomatium dissectum* var. *dissectum*), yellow montane violet (*Viola praemorsa* ssp. *praemorsa*), common ringlet (*Coenonympha california* ssp. *insulana*), sharp-tailed snake (*Contia tenuis*) (Garry Oak Ecosystem Recovery Team, 2007b).

peat deposits, “rough stony land” and gravelly sandy loam (Day *et al.*, 1959, and accompanying maps).

Blenkinsop Lake, near the headwaters of the watershed, is fed by seasonal streams; Blenkinsop Creek flows south from this lake, is joined by several first-order streams (today, more accurately described as ditches), and connects with Swan Lake (Figure 1.1). Some portions of Blenkinsop Creek have been enclosed in stormwater pipes in the Quadra St./MacKenzie Ave. area. Swan Lake is also fed by a number of stormwater pipes that discharge directly into wetlands surrounding the lake, forming short streams. One of these, a first order stream called Leeds Creek, joins with Blenkinsop Creek before it enters Swan Lake. Another has been called Darwin Creek, and enters Swan Lake wetlands near the municipal hall. (The remainder have not been named.) The only surface water outflow from Swan Lake is called Swan Creek. It flows west under the Patricia Bay highway, jogs to the north near McKenzie Ave., then meanders westward to join with Colquitz Creek, about 1.5 km upstream of its discharge point in Portage Inlet. Swan Creek is joined by a few small stormwater systems, and is a second-order stream.



Dec 2008. Lise Townsend, M.Sc. Candidate, University of Victoria. Orthophoto and GIS support provided by the Capital Regional District

Figure 1.1. Swan Lake watershed 2007 orthophoto (open channels shown in blue; culverts in red)

1.3. Literature Review: Ecological Health and Resilience

The concept of ecological health provides what many view as a scientifically valid metaphor that is intuitively understandable by the general public and scientists alike (Costanza *et al.*, 1992; Schaefer, 2006; Karr, 1999). However, there are few accepted standards and indices with which to evaluate ecological health (e.g. Kelly and Harwell, 1990). Some researchers are opposed to using the term at all, or object to the comparison with human health, e.g. asserting that equilibrium (i.e. homeostasis) is implied in so doing, belying the complexity of ecosystems (Ehrenfield, 1992; Callicott *et al.*, 1997; De Leo and Levin, 1997; Schaeffer *et al.,* 1988; Rapport, 1992). Others suggest that the term "health" should only be used to describe the ability of an ecosystem to provide services of benefit to people, while "integrity" is a term more appropriate for objective scientific assessment (Scrimgeour and Wicklum, 1996; De Leo and Levin, 1997). It is worth noting however that such debates usually centre on the "western medicine" approach to health, which generally focuses on single causal agents of disease, sometimes at the expense of more integrated perspectives (Temple and Burkitt, 1991; McKee, 1988). Eastern health paradigms (e.g. Traditional Chinese Medicine), in contrast, generally seek to elucidate patterns and processes (Kaptchuk, 1983), and could therefore help to address some shortcomings of equilibrium-based theory, an idea taken up in Chapter 6.

Advances in ecology and other sciences currently challenge the long-held view that ecosystems function at equilibrium ("the balance of nature") (Wu and Loucks, 1995). In this still-pervasive view, variability is assumed to be averaged over space and time, disturbance is a result of exogenous factors - and is usually undesirable - and the system returns to equilibrium following a disturbance (Holling, 1986). Clements' (1916) theory of succession was developed within such a paradigm: ecosystems are seen to develop in a predictable and linear fashion, beginning with the quick-establishing "pioneer" organisms and evolving to a climax stage, where long-lived organisms dominate and the landscape is essentially unchanging. Although these explanations are not wholly incorrect, they are now commonly seen as incomplete, since equilibrium in ecosystems is in fact rarely observed at any meaningful scale (Wu and Loucks, 1995; Holling, 1986; Schneider and

Kay, 1994).

Instead of constancy, ecosystems often exhibit spatial and temporal “patchiness,” and a hierarchical, nested structure (O'Neill *et al.*, 1989; Green and Sadedin, 2005, Holling, 2001). Holling (1992) showed that ecosystems are controlled by a set of relatively few variables at various scales, and that interactions across scales result in nonlinear behaviour. Most ecosystems at some scale depend on disturbance as a renewal agent that helps the system to persist (Pickett and White, 1985; Gunderson and Holling, 2002). Beneficial effects of disturbance have been observed in wetlands (van der Valk and Davis, 1978), streams (Reice *et al.*, 1990; Reeves *et al.*, 1996), grazing and fire-dominated landscapes (Folke *et al*., 2004). This is important for ecosystem management and restoration; human management that is designed to maximize the constant yield of a desirable resource, and to limit variability, may inadvertently cause the system to collapse (Holling and Meffe, 1996).

Studies of thermodynamics and energy substantiate this point of view, characterising ecosystems as open, nonlinear, systems that function *far from equilibrium* to dissipate or degrade energy gradients (Schneider and Kay, 1994; Capra, 1996; Ulanowicz, 2003). For example, Schneider and Kay (1994) quantified the matter/energy partitioning and exergy[3] flows through a system, to make inferences about ecosystem properties, such as developmental stage and system stress. They listed properties of more “mature” ecosystems, similar to E.P. Odum's (1969) attributes of ecosystem development, some of which can be used to help characterise ecosystem health, as discussed in Chapter 6. Similarly, Ulanowicz (1986) developed the concept of *ascendency*, which is a measure of a system's level of activity and degree of organisation, calculated as system throughput. Thus a “leaky” system does not cycle matter and energy efficiently, compared to a reference system, potentially indicating stress (Schneider and Kay, 1994). Energy-based analyses have been applied to evaluate efficiency and sustainability in coupled human-ecosystems, for example demonstrating how excessive energy inputs in highly industrialized systems have caused environmental destruction, compared to ecologically

3 Exergy refers to the ability to do “useful” work, i.e. it is a measure of the quality of energy available (Schneider and Kay, 1994).

based management that more effectively dissipates energy and supports biodiversity (e.g. Ho and Ulanowicz, 2005; Odum, 2007; Yang *et al.*, 2003). Quantification of solar energy dissipation has also been applied to evaluate ecological stresses from land use activities including vegetation clearing and the urban heat island effect (Luvall and Holbo, 1989; Lo *et al.*, 1997; Weng, 2006; Ripl and Hildmann, 2000; Pokorný, 2001; Procházka *et al.*, 2001). Ecosystem 'development' in these examples nevertheless appears to rest on the linear view of succession, assuming a climax of maturity at which point energy dissipation is maximized, and while valuable for characterising disturbances and encouraging more sustainable resource management, these concepts may not be sufficient alone to evaluate “resilience.”

The concept of ecological resilience presents a view of ecosystem development that accounts for cyclic disturbance and other patterns of variability, and may help advance alternatives to an equilibrium-based perspective. Holling (1973) first defined resilience as “the ability of [ecosystems] to absorb changes of state variables, driving variables, and parameters, and still persist.” Persistence can be seen as a system being defined by a particular configuration or domain of attraction in phase space, a mathematical and graphical construct (Walker *et al.*, 2004). The idea was founded on detailed studies of predator-prey dynamics, but also on general observations about diverse ecosystems. These concepts generated a wide body of work by Holling and many other researchers, and have been applied to social as well as ecological systems (Resilience Alliance website, 2008).

Key concepts in resilience theory are complexity, non-linear behaviour and multiple stable states. Complex systems can have more than one stability domain, and a system can suddenly 'flip' to a different domain due to slow variables or exogenous factors (Holling, 1986). This can be illustrated by a ball and cup diagram (*e.g.* Sheffer, 2004; Walker *et al.*, 2004; see also Chapters 3 and 6), showing how a system's position within a particular stable state can be pushed into a different state with internal or external stress. This often results in dramatically different characteristics, for example in the case of shallow lakes shifting from clear water to turbid water (Walker *et al.,* 2004). This shift often occurs in response to nutrient loading from agriculture and urban development; each condition is resilient within certain parameters, however the turbid state has proven to be quite resistant to shifting back to clear water (Scheffer *et al.*, 2001; Scheffer, 2004; Carpenter and Cottingham, 1997). This particular process is highly relevant to Swan Lake, as discussed in Chapter 5, however there may be other examples of multiple stable states in the watershed, as discussed in Chapter 6. Thus it is clear that resilience is value-free, in that various stable states may be resilient.

Systems that exhibit alternative stable states include savannas in Africa and North America (Walker *et al.,* 1981), wetlands such as the Everglades (Gunderson, 1999), temperate forests (Drever *et al.,* 2006) and coral reefs (Hughes *et al.*, 2003; Grimsditch and Salm, 2006).[4] The Province of B.C. has incorporated resilience as a forest management goal (B.C. Ministry of Forests, 2006).

It is important to note that the term resilience is sometimes also used in a different way, to mean the ability of a system to return to an *equilibrium* after a disturbance (e.g Steinman *et al.*, 1991; Kaufman, 1982; DeAngelis *et al.*, 1989). Holling (1996) calls this type of behaviour "engineering resilience" as opposed to "ecological resilience," which is discussed here.[5] A final concept important to the theory of resilience is how it relates to ecosystem development. Holling (1992, 2001) outlines a four-stage "figure eight" cyclical pattern of ecosystem development, which was referred to as the adaptive renewal cycle, and later called Panarchy (Gunderson and Holling, 2002). This cycle includes the r- and K stages typical of Clementsian succession, but adds the "release" (Ω) and "reorganization" (α) phases, wherein potential energy (e.g. accumulated nutrients or biomass) is released by a disturbance, and new developmental trajectories are available. Although the adaptive renewal cycle is not stated to be universally applicable, numerous

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4 Alternative stable states in these systems may include grasslands vs. shrub lands (depending on grazing influence), dominated by alternative wetland species depending on nutrient regime, structurally diverse vs. homogenous (depending on fire frequency), and dominated by algae vs. low in algae and more diverse (depending on grazing by fish and nutrient regime) (see above-cited references).

5 Engineering resilience is useful for studying linear systems, or for some nonlinear systems where disturbances are small in spatial/time scales, however for complex systems subject to large disturbances, return time is less relevant (Carpenter and Cottingham, 1997).

ecosystems appear to exhibit these kinds of changes, whether on small/localised or large/infrequent scales (Walker *et al.,* 2004; Scheffer *et al.*, 2001; Folke *et al.*, 2004). Along with other ecological processes, this cycle serves to dissipate and redistribute energy and matter in the landscape, as discussed later.

The concept of, and principles behind resilience have proven to be useful for describing how ecosystems (and social-ecological systems) function and develop, particularly as an alternative to narrow, stability-based views that predominated before. They have helped to show that when ecosystems are managed as if they were predictable and deterministic, for example in maintaining constant "maximum sustainable yields," large-scale collapse often results (Holling and Meffe, 1996). In this sense, resilience and adaptive renewal have opened up new resource management approaches based on respect for complexity and variability (Berkes *et al.*, 2003). Cumming and Collier (2005) state that "Holling's adaptive cycle is one of the few well-defined, well-supported interpretations of complex system dynamics." However, the concept of resilience is difficult to "operationalize" and there are as yet few tools or metrics to assess resilience, except after a system has collapsed (Carpenter *et al.*, 2001).

Generally, cities are hubs of technology and dense human infrastructure forming rigid landscapes that in many cases have shown limited capacity for adaptation to large-scale social and ecological disturbances (Andersson, 2006; Redman and Kinzig, 2003). Therefore the concept of resilience is particularly relevant to urban ecology. Yet, with a few exceptions (e.g. Alberti, 2005; Alberti and Marzluff, 2004), detailed studies applying resilience theory to urban ecosystems are rare.

1.3.1. Assessing Ecological Health and Resilience

There are many methods that are available to measure the energetic attributes of ecological systems. For example, ecosystem ascendency (Ulanowicz, 1986) appears to be a useful and well-supported measure of ecosystem processes, particularly to address ecological complexity. However, extensive data is required to model an entire ecosystem, requiring a great deal of effort and expense (Leibowitz *et al.,* 2000; Ulanowicz, 1992).

This level of detail may provide valuable information, representing a rich area for current and future research, particularly in computer modelling (e.g. Heymans *et al.*, 2002; Baird *et al*., 1995). However, a suite of fewer indicators that integrate some of the more complex ecological processes, and that are possible to study with standard ecological techniques, would be useful for restoration ecologists and resource managers.

Energy-based indicators of ecological health also appear to neglect cyclical patterns, and the importance of disturbance as a necessary and inevitable process (for most systems). For example, Müller (2005) represents ecosystem development with ever-increasing exergy capture, complexity and connectedness, without accounting for the inevitable collapse of the model. Similarly, many of the properties of developing ecosystems as proposed by Schneider and Kay (1994) and E.P. Odum (1969) seem to portray the *r* and *K* stages of succession, without accounting for ecological resilience in the ability to remain in a particular stability domain. However, energy analysis could provide valuable information about the position of a particular system along this trajectory (e.g. Bormann and Likens, 1979). Additional indicators may therefore be required to account for other properties of self-organizing systems in an integrated fashion.

One of the most widely cited methods for evaluating ecological "integrity" is the Index of Biotic Integrity (IBI) which is applied to to streams and incorporates attributes of fish or invertebrate communities (Karr and Chu, 1999). However, such systems do not apply to terrestrial ecosystems, nor to a mixture of both terrestrial and aquatic ecosystems (Andreason *et al.* 2001).

Costanza (1992) proposed a system health index, one of the more commonly applied methods (e.g. Xu *et al.*, 2001; Liu, Yang and Chen, 2007; Jørgensen, 2004). However, this index is not yet broadly accepted in the scientific and management communities, and can be difficult to put into practice (Boesch and Paul, 2001; Karr, 1999).[6]

In the midwestern U.S.A., the concept of "rangeland health" was developed in response

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6 Furthermore, quantifying resilience in this method involves combining the two definitions of resilience (return time and ecological resilience) (Costanza and Mageau, 1999), which seems a questionable practice given the divergent underlying assumptions as discussed above.

to severe over-grazing and erosion that reduced the livestock value of the landscape, and is widely employed by federal resource management agencies (West, 2003; NRC, 1994). Definitions and concepts of some methods are however still strongly influenced by Clementsian succession theory and have been criticised for their failure to incorporate alternative views of ecosystem development (West, 2003; NRC, 1994). The National Research Council (1994) recommended instead a system for assessing rangeland health that recognises thresholds (multiple equilibria in the sense of ecological resilience) and is based on a threefold assessment of: soil stability and watershed function; nutrients and energy flow; and recovery mechanisms. This system appears to be one of the few available for evaluating ecological health that is based on dynamic systems theory, as well as on practical and easily observed field indicators (Pellant *et al.*, 2000). However, as it was developed for shrub- and grasslands, it is not clear if and how the system may be applied to other types of landscapes, including urban areas.

One method that is widely used for assessing the health of freshwater streams and wetlands is called *Proper Functioning Condition* (PFC) (Prichard, 1998). PFC was developed by scientists with the U.S. Bureau of Land Management, Fish and Wildlife Service and Natural Resources Conservation Service, originally to assess rangeland streams and wetlands that were primarily subjected to disturbances from grazing and logging. PFC consists of a field assessment conducted by an interdisciplinary team, to determine the health of a stream or riparian area based on physical characteristics grouped under the headings of *hydrology, vegetation* and *soils*. A system that is "functioning properly" according to this system has the required elements in these categories to withstand disturbance and perform a variety of important ecosystem services (Prichard, 1998). Despite the limitation of some basis in linear succession theory, PFC provides a useful tool, as discussed in Chapter 3. Nevertheless, PFC is applicable only to freshwater ecosystems, not to terrestrial systems, and therefore may not be sufficient to characterise the overall health of a watershed. Some attributes of PFC are applied in this larger context in Chapter 6, in a set of proposed criteria.

As stated above, resilience is a promising concept, but practical indicators of resilience are needed. Some recommended or proposed methods for evaluating an ecosystem's present resilience or stage in the adaptive cycle include the following.

- Carpenter and Cottingham (1997) proposed several "surrogate" metrics for ecological resilience in lakes. These include: livestock density (indicative of phosphorus loading in an agricultural setting); wetland area per lake area; proportion of riparian zone occupied by native vegetation; lake colour; piscivore growth rates (indicative of planktivore control); grazer body size (correlated with the capacity to control agal growth); partial pressure of CO_2 (an indicator of ecosystem metabolism); and hypolimnetic oxygen levels (low levels indicate eutrophication).

- Carpenter *et al.* (2001) suggest a practical measure of resilience would need to assess the slowly changing variables in a system, such as (for lakes) phosphorus levels in sediments and in catchment soils.

- Cumming *et al.* (2005) suggest a "surrogate" assessment for resilience can be obtained through a collaborative process involving stakeholders, to characterise system elements, drivers and relationships, and assess the likelihood of various changes and trajectories of the system. The "measure" of resilience in this case is therefore only a relative estimation of the probability of various outcomes. This process also assumes that the stakeholders have a good understanding of the system dynamics.

- Bennett *et al.* (2005) recommend choosing surrogates for resilience based on a systems model. Surrogates include: distance of the state variable from the threshold (e.g. P concentration of a eutrophic lake, relative to P loading); sensitivity of the system to further movement (e.g. amount of P recyling); the rate at which the state variable is moving toward or away from that threshold (e.g. rate of change in terrestrial P inputs). The authors recommend that these process variables be characterised and chosen by several small and diverse research teams (Bennett *et al.*, 2005), however it is unclear how these variables and changes would be measured. Furthermore, the process of defining the "desired" state does not stipulate a scientific basis, such as within the historical range of variability, that could help to prevent creation or maintenance of an ecologically unhealthy system.

- Allen *et al.* (2005) propose quantifying the composition of and discontinuities among functional groups comprising a system, based on the evidence that ecosystems consist of nested hierarchical structures, as discussed previously (*e.g.* Holling, 1992). System components could be animal body size, or the size of urban areas. Simple statistics and graphing could be used such as richness, diversity, and rank/enumeration. The authors cite one example of a study that has used such a metric, however they acknowledge the need for more research.
- The Resilience Alliance (2007a and 2007b) has published two workbooks outlining a process to assess and manage resilience in social-ecological systems, involving a multi-disciplinary and multi-stakeholder process to define the system boundaries and spatial/temporal scale of the inquiry and characterise the system in question. Key steps include historical research, identifying system drivers, disturbances, key players (individuals and organisations) and governance structures, developing system models, identifying possible alternate regimes and thresholds, and finally outlining management strategies for the system. This process entails an investigative and management approach, but does not purport to quantify resilience.

In summary, there are no widely applied methods currently in use to quantify resilience as a single variable, however there are several processes that could be (or have been) used to examine system properties based on resilience concepts.

1.4. Approach and Research Questions

The concept of ecological health is subject to ongoing debate; however, it is a term that can capture the attention and concern of the public, something that is sorely needed in order to address the critical condition of ecosystems worldwide. Ecological resilience offers a set of concepts and theory to reconcile the dynamic and nonlinear behaviour of ecosystems with management strategies that support, rather than undermine, ecological health. As explained in Chapter 6, ecological health is defined for the purpose of this thesis as:

The development of ecosystem structures, functions and composition that serve to dissipate energy gradients, within a cycle of adaptive renewal consistent with the historic range of variability, where resilience is maintained around a desired stable state.

Ecological resilience in turn refers to the ability of a system to absorb disturbances without shifting to an alternative stable state (e.g. Walker *et al.,* 2004).

Due to the limitations of this study, assessment methods requiring extensive data collection, complex computer modelling and long-term study were not employed. Energy-based indicators such as ascendency, exergy and emergy (Odum, 2007) were therefore beyond the capability of this researcher and this project, as was Costanza's (1992) health index, as it is based on modelling procedures. However, I discuss some of the findings of the study in terms related to nonlinear thermodynamic principles, as the theories provide some valuable insights to complex systems. In particular, loading of nutrients and dissolved solids, and evapotranspiration by vegetation at the watershed scale, are relevant indicators of landscape 'health' and resilience.

A characterisation of ecological resilience according to the methods outlined by the Resilience Alliance (2007a and 2007b) involves extensive stakeholder involvement and interdisciplinary research teams. Although this appears to be a valid approach, I lacked the resources to complete both an ecological study and a community/stakeholder engagement process. I chose to pursue the former, with the rationale that it could provide a basis for a more integrated social-ecological study in the future. Nevertheless, I have applied the underlying theory of resilience to frame my approach, and therefore draw inferences about various components and processes of the watershed in these terms.

Proper Functioning Condition is an applicable method that enables fairly rapid field evaluations, despite some limitations, therefore I carried out assessments of the main streams in the watershed, in an interdisciplinary team with Aqua-Tex Scientific Consulting Ltd., a sponsor of my research. The degree to which PFC fits with resilience theory was also explored, as discussed in Chapter 3.

Although streams can be good indicators of watershed processes, I opted to use a more inclusive system in order to more comprehensively evaluate the health of the watershed as a whole. I did not find such a tool, therefore I developed a preliminary framework for this purpose as described in Chapter 6. In this and other findings, this study therefore contributes to the as-yet nascent body of research surrounding applications of resilience theory to urban landscapes. General findings and assessment techniques could be applied in other areas to enable development and management policy that supports the mutual objectives of improved ecological and social/economic health.

In order to better understand complex social-ecological systems, the watershed provides one of the most relevant scales at which to study and manage urban and non-urban systems alike (Krauze and Wagner, 2008). A watershed is a "drainage basin," (Canadian Oxford Dictionary, 2004), i.e. an area of land that supplies surface and groundwater to a particular water body. A large watershed can in turn be described as a nested structure of self-similar, smaller units (sub-watersheds). The water cycle and living organisms mediate flows of energy and matter throughout the watershed (Ripl, 2003). In particular, green plants play a fundamental role in providing the fuel (biomass), structure and atmospheric conditions necessary to support other life forms. Therefore, in this thesis I have taken a watershed perspective to better understand the interrelationships between various ecosystems and the people that inhabit them, and have in particular focused on vegetation and water. The term "eco-hydrology" (which forms part of the title of this thesis) refers to the study of integrated processes of water and plants at the landscape scale (Zalewski, 2002).

The following research questions address the above-stated overall hypothesis.

1. Based on available information, what were the main ecological attributes and processes in Swan Lake watershed in the past? How did people manage and

interact with them? (Chapter 2)

2. How do components of Swan Lake watershed function today, according to vegetation and water-related studies? How do these studies help to evaluate ecological health and/or resilience? (Chapters 3, 4 and 5)

3. Based on the findings of the study, how could ecological health and resilience be assessed in an urban watershed? Is Swan Lake watershed healthy and resilient to disturbances according to these criteria? (Chapter 6)

4. How might future systems in Swan Lake watershed be managed to maintain or restore ecological health and resilience? (Chapter 6)

The discussion in the chapters that follow are built around the following main research components.

- A detailed investigation of the landscape history, including a paleoecological study of pollen samples from the wetlands at Swan Lake, First Nations management and ecologically relevant changes since the beginnings of urban development (Chapter 2). This historical inquiry is important to establish reference conditions, for comprehending how urbanisation subsequently affected watershed processes.

- An assessment of the existing physical function of the main-stem stream channels in the watershed (Chapter 3). Since streams receive flows (water, nutrients and other matter) from upland areas, their condition can help to reveal concerns at the watershed scale.

- Characterisation of the vegetation communities in the wetlands of the study area, as well as land cover across the watershed, and comparison with historical information (Chapter 4). Based on historical and present vegetation characteristics, a pilot restoration project using native willow plantings to replace invasive reed canary grass is summarised in Appendix C. Swan Lake includes the largest remaining wetland in the watershed, which as a keystone ecosystem has importance at the site and watershed scale.

- Hydrological measurements of surface water flows in the inflow stream, outflow stream, and lake of the focal area of the study, including limited water quality analysis (Chapter 5). Aquatic ecosystems are strongly influenced by the timing and duration of both high and low flows, and urbanisation typically strongly influences these patterns.
- A synthesis discussion of resilience concepts based on the findings from the preceding chapters, and a proposed set of criteria for assessing the ecological health of an urban watershed, using Swan Lake watershed as a case study, including recommendations and conclusions (Chapter 6). Since the scope of this study was limited in time and intensity, possible methods for a more complete understanding of ecological health and resilience are proposed. The conclusion outlines an approach to management and development in this watershed (and general principles applicable to other areas) that is based on mimicking natural water and energy cycles.

Chapter 2. History of Landscape Processes and Human Influences in Swan Lake Watershed, ca. 1850 to Present

Understanding landscape history is critical to comprehending ecological function, for example ascertaining a system's position along a continuum of change, and its ability to respond to shocks and disturbances (Resilience Alliance, 2007a). Ignorance of the past can lead to harmful actions, for example by either intervening in natural ecosystem recovery or “preserving” what is in fact a degraded ecosystem (e.g. Swetnam et al., 1999). On the other hand, historical ecological inquiry can increase understanding of biotic and abiotic processes that shape the landscape, and aid in setting appropriate restoration targets, thus placing a present day scientific study in the proper context. In order to address the nonlinear, open and dynamic nature of ecosystems, processes and functions should be emphasised over “states,” requiring an investigation into the historic range of variation rather than a static picture of the past (DeLeo and Levin, 1997; Egan and Howell, 2001). Despite the challenges of sifting through inherently biased maps, anecdotes and stories, this exercise is vital to achieving a deep understanding of changes that have occurred.

This chapter focuses on some of the landscape characteristics of Victoria and Swan Lake watershed, prior to and around the time of European settlement and upon becoming subject to modern patterns of development, in order to understand how human-wrought changes have affected ecosystem processes. This information can be used to inform strategies for restoration and (re-) development to improve ecological health, as discussed in Chapter 6. A paleoecology study was also carried out, in order to characterise the pre-development species composition of Swan Lake wetlands, which, as a 'keystone' ecosystem in the watershed, perform important functions at both the site and watershed scale (Townsend and Hebda, in Progress; Appendix A). The results of that study are already being applied to help establish restoration targets and management strategies at Swan Lake Christmas Hill Nature Sanctuary.

2.1. First Peoples of Southern Vancouver Island and Victoria

The popular myth that the first Europeans in North America arrived in a “virgin” or “pristine” land has now been largely discredited; rather, a large native population carried out deliberate ecosystem management in many, if not most, areas of North America (Mann, 2002; Van Lear and Wurtz, 2005; Daniels, 1992). This resulted in co-evolution of cultural systems and ecosystems; for example, people influenced community composition and genetic adaptations, by maintaining certain environmental conditions, and through selectively harvesting and hunting (Abella, 2007; Barsh, 2003). Therefore, it is important to elucidate cultural influences on landscape function. People have the capacity not only to degrade ecosystems, but also to enhance resilience through sustainable management. This applies both in the historical context and today.

People have lived in coastal B.C. since at least ca. 8,000 to 9,000 years ago (Muckle, 1998), and possibly earlier (e.g. Hetherington *et al*., 2004). Some of the oldest archaeological sites in the Victoria area have been dated to around 4,150 years before present (Keddie, 2006). In the area of Victoria and the San Juan/Gulf Islands, indigenous people belong to the Northern Straits language group, dialects of which include *Lekw'iní?nen*, *Sencoten* and *Xwlemichosen*; these include today’s Songhees, Saanich, T’Souke and Lummi (Keddie, 2003). In the Victoria area, villages are believed to have existed at a large number of sites prior to European contact.[1] There appears to be little information about the pre-historic use of Swan Lake itself by Songhees and/or Saanich peoples.[2]

In the past, indigenous populations were often thought to have been inconsequential and therefore to have had little effect upon the landscape. However, modern re-assessments, based for example upon epidemiology to estimate mortality from European-introduced

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1 Known local village sites include: the San Juan and Gulf Islands; Brentwood Bay; Beecher Bay; Parry Bay; Patricia Bay; Saanichton Bay; Esquimalt Harbour; Victoria Harbour; the Gorge; Cadboro Bay; Discovery Island; Cordova Bay; Portage Inlet; McNeil Bay; Ross Bay; Shoal Bay; Gonzales Point; and Willows Beach (Suttles, 1990; Keddie, 2003; Duff, 1969; Hill-Tout, 1907; Jenness, 1934-35).

2 One rare anecdote is that a knoll on the NE side of Swan Lake was reputedly used for catching waterfowl with a pole-mounted net (Keddie, pers. comm.). As with all wildlife, a huge variety and abundance of migratory and resident waterfowl and other types of birds were historically present (e.g. Grant, 1857).

diseases, suggest otherwise (e.g. Boyd, 1999a). The population of the northwest coast in general has been estimated at 200,000 to 300,000, based on archaeological midden sites (Hebda and Frederick, 1990), while Boyd (1999a) proposed a range between 183,661 and 400,000. Locally, the indigenous population of Vancouver Island was estimated at 17,000 by W.C. Grant (1857), while Hill-tout (1907) estimated the Songhees to have numbered 8,500 prior to 1860 (using the more updated methodology of Boyd (1999a), Hill-Tout's numbers should be adjusted upwards to ~11,000 prior to the first two epidemics). Despite the variability in these numbers, they suggest a substantial population that had the potential to affect the abundance and distribution of wildlife and vegetation, requiring a conservation “ethic” to prevent over-harvesting (Jones, 1996).

Fishing and hunting were major subsistence and economic activities (Suttles, 1990); in addition, over 300 species of plants were used for food, medicines and materials and were crucial to indigenous peoples’ survival and culture (Turner and Peacock, 2005). The opportunistic “hunter-gatherer” stereotype is increasingly seen as overly simplistic, as sophisticated cultivation techniques were used, included prescribed fire, harvesting and replanting, digging and tilling, tending and weeding, sowing and transplanting, and pruning and coppicing, and affected the distribution and composition of vegetation communities across the landscape (Turner and Peacock, 2005).

Cultivation in some cases established a creative cycle, where the harvesting techniques increased the productivity of desired plants, and helped to create a diverse mosaic of age classes and community types (Turner *et al.,* 2003; Anderson, 1999; Lake, 2007). For example, willow was widely used locally for the reef net fishery,[3] and due to the cultural importance of this technique (by a relatively large population as discussed above), large-scale harvesting is likely to have had significant effects on wetland vegetation structure in areas such as Swan Lake. This can be stated based on evidence from studies in California showing a positive response by willow and other riparian shrubs to repeated harvesting for indigenous uses (Anderson, 1999; Lake, 2007). A rough estimate suggests that between 750 and 1688 metres of willow shoots (approximately 1-3 cm diameter) would

3 The reef net is a technique for offshore salmon fishing: a large net was traditionally woven from willow bark, and suspended in the water between two canoes (Claxton, 2004).

have been required for a single reef net (Townsend *et al.*, In Progress). This principle of human management with ancillary ecological benefits can be exploited for restoration at Swan Lake, and a pilot project has been carried out using willow with a particular planting and mulching technique to control invasive reed canarygrass and establish a source of materials for cultural use (Townsend *et al.*, In Progress; Appendix D).

2.2. Early European Settlement and Landscape Characteristics

In 1837, Hudson's Bay Company (HBC) Captain McNeil sailed into Victoria Harbour, in search of a location for a HBC post, and in 1842 James Douglas and others disembarked for the first time in Cadboro Bay (Keddie, 2003). In 1843, Fort Victoria was constructed, a small amount of land was put into cultivation, and in the decades that followed, concerted effort at colonization and city-building began. In 1850 and 1852, Sir James Douglas, Chief Factor of the HBC, and later Governor of British Columbia, signed treaties with the Songhees and Saanich peoples, stipulating trade of their lands in exchange for payment (in blankets) and guaranteed rights to hunt and fish "as formerly" (Bowsfield, 1979). Indian Reserves were established in 1876, which set the extent of the lands allocated to First Nations (UBCIC, no date). These developments did not signal an end to indigenous culture, as many First Nations to this day work to retain and revive their traditions and languages and continue to challenge the loss of their lands and access to resources (Harris, 2002). However, in terms of resource management, since the Douglas treaties and the reserve system were put in place, Europeans largely determined the trajectory of change in the local landscape.

The Victoria Official Map of 1858 (Figure 2.1)[4] is one of the oldest maps that is relatively to-scale and that also includes information about vegetation cover. This map depicts four different ecosystems[5]: lakes and stream channels; "swamp" and riparian corridors; conifer forest; and open deciduous forest, interpreted as savanna/woodland

4 Obtained from the B.C. Land Titles Office, 32Tr.2 (authors unknown)

5 Although the map does not include a legend, vegetation communities are inferred from landscape position, correlation with other sources, and common usage of certain symbols (e.g. stars to indicate conifers).

dominated by Garry oak. A more detailed version of this map, highlighting the current extent of Swan Lake watershed, is shown in Chapter 4.

Figure 2.1. Victoria Official Map, 1858, with wetlands and riparian corridors highlighted (see text for numbered features), most of which are no longer present

2.2.1. Terrestrial Ecosystems

Garry oak ecosystems, consisting of widely spaced oak trees with a shrub or herbaceous understory, were a major feature of the local historical landscape, and enthralled early European explorers who compared them to a manicured English “park” (Pethick, 1968; Beckwith, 2004). Although present since ca. 7000 years ago when the climate was warmer and drier, Garry oak ecosystems have persisted until modern times likely due in large part to burning by First Nations (Gedalof *et al.*, 2006). Indigenous peoples used techniques including fire and other cultivation to encourage production of camas (*Camassia* spp.) and other food plants associated with these ecosystems (Turner, 1999; Turner and Peacock, 2005; Beckwith, 2004). Garry oak ecosystems are shown in one of the earliest maps of the region as large "plains," especially throughout Victoria and Oak Bay, but also including parts of Swan Lake watershed (Lewes, 1842). In addition to oak trees and camas, Garry oak ecosystems included abundant wildflowers and diverse other shrubs, ferns, forbs and grasses (Fuchs, 2001; Beckwith, 2004)[6].

The second major terrestrial land cover historically was a Douglas-fir-dominated forest that also included various other trees, and usually a shrub understory.[7] Several historical descriptions emphasize the abundant berries and openness of the understory (e.g. Pritchard, 1990), suggesting frequent low-intensity fires (Turner, 1999). Landscape burning by indigenous people is also well documented in the Willamette Valley, on the San Juan Islands and in southwestern Washington (Boyd, 1999c; Leopold and Boyd, 1999: Barsh, 2003).

2.2.2. Wetlands, Lakes and Streams

The 1858 Official Victoria Map (Figure 2.1) shows numerous wetlands and riparian corridors in the Victoria District , including: Swan Lake (#1 on map), Blenkinsop Lake (2), Douglas Creek (3), Mystic Vale (4), Bowker Creek (5), Fairfield (6), and Panama Flats along Colquitz Creek (7). A map from 1859 (James, 1859; not shown) shows a portion of the Lake District to the north of Swan Lake watershed, including Elk Lake and

6 Common shrubs included snowberry (*Symphoricarpos albus*), Nootka rose (*Rosa nutkana*), oceanspray (*Holodiscus discolor*), Oregon grape (*Mahonia* spp.), Indian plum (Oemleria cerasiformis), saskatoonberry (Amelanchier alnifolia) and others. The principal fern in the open areas was bracken fern (Pteridium aquilinum), which was used as a food source by indigenous people in western Washington as well as in this area (Norton 1979, 1980; Turner, 1998).

7 Common trees included western redcedar, grand fir and bigleaf maple (*Acer macrophyllum*), while lodgepole pine grew in drier and higher elevation sites; understory species were predominantly shrubs such as salal (*Gaultheria shallon*), salmonberry, red flowering currant (*Ribes sanguineum*), trailing blackberry (*Rubus ursinus*), saskatoon berry, red huckleberry (*Vaccinium parvifolium*) and thimbleberry (*Rubus parviflorus*); diverse herbaceous species and flowering perennials were also common (Pemberton, 1860; Bayley, 1878; Grant, 1867).

Beaver Lake connected by braided channels[8], which surveyor Thomas Buckley in 1872 described as a "stretch of willow swamp" (Pearson, 1981).

Although salmon were plentiful even in some small local streams, it appears that the British were unimpressed with Vancouver Island's streams, perhaps in comparison to the Fraser River or to large European rivers, and as noted by Forbes (1894, p. 155), "*... in no case does the watershed suffice to give a navigable stream. There are no rivers, in the stricter sense of the word, such streams as flow through the country being simply the short watercourses, which discharge the overflow of lakes or the surface-waters of the neighbouring ridges - torrents in winter, nearly dry in summer...*"

The above passage illustrates that the pre-disturbance condition of many streams in the area was evidently one of seasonal flows. Southeast Vancouver Island receives much less rainfall than areas to the west and north along the coast, and summers can be particularly dry, as noted in Chapter 1. The low relief of the land and does not allow for water storage in mountain lakes and ice caps. Therefore surface runoff is generally low except in high rainfall events in winter, and the extensive network of wetlands shown in Figure 2.1 would have been important for maintaining summer stream flows and associated biodiversity.

The vegetation composition of the wetlands is not apparent from the maps, and surveyors' notes for the study area are not available, however wetland species and general characteristics for the region can be derived from other sources.

- Several wetland types are mentioned in J.W. Trutch's (1859) survey notes for the Central Saanich area: "willow swamp" is by far the most common (27 incidences out of 53 total wetland-related notations), sometimes including crabapple; it is followed by cedar and/or spruce swamp (9), low rush and grass bottom (6), "brushy" swamp or wet areas (4), and alder and/or cottonwood "swales" or flats (4). Unique combinations include "crabapple, willow and briers," "willow &

8 This map also includes descriptive notations about the landscape such as "open prairie," and "thick growth of pine [Douglas-fir] and cedar."

spruce & cedar swamp," and "cedar spruce and cranberry swamp." (The remainder are unspecified swamps.)

- Willow and alder are frequently mentioned in historical descriptions, for example as described by Fawcett (1912): "*After you left Blanshard Street, the way to the school* [near present-day Central High School] *was by a pathway through the woods. The country around View and Fort Streets, up to Cook, was very swampy, and covered mostly by willow and alder trees. In fact there was a small swamp or lake on View Street, where there was good duck shooting in winter."*
- Present day Clover Point[9] was once called "Wholaylch" by the Songhees, meaning "willows" (Duff, 1969, p.45). "Ku-sing-ay-las" meaning "the place of the strong fibre," refers to the Pacific willow and its use for the reef net, and was associated with two areas around Fort Victoria (Keddie, 2003).[10] J.R. Anderson's memoirs (1912) state that the area later occupied by Fort Victoria was called "Kwahl-sn-ELA" by the native people, possibly the same name.
- A large wetland was present south of Blenkinsop Lake, consisting at least in part of "over six hundred acres covered with water and partly covered with willow trees," and contained Labrador tea (*Ledum groenlandicum*) (Irvine, 1942). Hardy's (1956) detailed inventory of remnant native species in this wetland includes Sphagnum, sundew, bog laurel, bulrush, pond lily, willow and alder. This wetland was cultivated and (presumably) drained since at least 1888, according to a map from that year.

These various wetland types, and possible modern classifications, are summarized in Table 2.1.

9 "Clover" now refers to springbank clover which also once grew there – N. Turner, pers. comm.)

10 J.R. Anderson's memoirs (1912) state that the area later occupied by Fort Victoria was called "Kwahl-sn-ELA" by the native people, which could be the same name.

Table 2.1. Summary of historical wetlands in Victoria and possible equivalent site identifiers as per McKenzie and Moran (2004)

Wetland type	Described by	Equivalent Site Identifier
willow swamp	Buckley, 1872 (in Pearson, 1981); Trutch, 1858	Ws51, Sitka willow - Pacific willow – skunk cabbage
willow and alder	Fawcett, 1912	Ws52, Red alder - skunk cabbage
cedar and/or spruce swamp	Trutch, 1858	Ws54, Western redcedar - Western hemlock - Skunk cabbage
rush and grass bottom	Trutch, 1858	Wm50, Sitka sedge - Hemlock parsley; Wf53, Slender sedge - White beak-rush
brushy swamp	Trutch, 1858	Ws50, Pink spirea - Sitka sedge
alder/cottonwood swales	Trutch, 1858	Fm50, Cottonwood - Red alder - Salmonberry
cedar, spruce, cranberry	Trutch, 1858	Wb50, Labrador tea - Bog laurel - peat-moss (possibly fringed with a swamp association containing cedar/spruce)
Sitka spruce, shore pine, Labrador tea, bog laurel, Sphagnum, sundew	Hardy, 1956	Wb50, Labrador tea - Bog laurel - peat-moss

With regard to Swan Lake and its inflow/outflow streams, there are similarly few early (pre-agricultural) descriptions of ecosystem characteristics, with the exception of the following:

- Blenkinsop Lake was not previously connected to Swan Lake with an open channel as it is today (Hardy, 1956). A channel was eventually dredged and blasted to better drain the Blenkinsop wetland, and was gradually deepened in a series of drainage “improvements,” connecting the area to the Swan Lake inflow stream (e.g. Saanich Archives, 1922; Saanich Archives, 1975).
- Swan Lake itself supported trout fishing near the turn of the 20th century (Swan Lake Nature Centre, 1994), and was a popular location for swimming (Castle, 1989), indicating that the water was probably clear and high in oxygen. This represents an alternative stable state to today's highly eutrophic conditions (Scheffer, 2004).

- Salmon spawning in Colquitz Creek in the fall were once "so thick you could just walk across them" (as stated by Bob Mercer sometime around or prior to 1909, quoted in Morrison, 1983).[11] Species included Chinook and Coho (Suttles, 1974).
- The Lake Hill property was subdivided into 5-acre lots in 1884 (Swan Lake Nature Centre, 1994). An undated list of the subdivided lots provides a brief description of each lot (B.C. Provincial Archives, no date). Some very general vegetation descriptions are listed in Table 2.2, corresponding to the map in Figure 2.2.
- One important feature of the landscape in these days was the wetland that previously existed at the outlet of Swan Lake, downstream as far as McKenzie Ave. This is mentioned in Table 2.2 next to lots 71, 72 and 73, and the swamp appears on the 1858 map (Figure 2.1). This area has since been drained. A timber lease for "cord wood" dated 1889 (BC Provincial Archives, 1889) includes several lots adjacent to Swan Creek (71, 72 & 73) , thus it can be assumed these contained substantial large conifer trees.
- In an anecdotal description from a resident living adjacent to Swan Lake between 1912 and 1928, species recalled include red alder, hardhack, crabapple and cascara, with Douglas-fir on rocky outcrops (Zaccarelli, 1975).

km

11 In contrast, today there are usually less than a few hundred fish returning to spawn (Victoria Fish and Game Protective Assn., pers. comm.).

Table 2.2. Examples of lot descriptions, Lake Hill Subdivision

Lot number	Description from subdivision document (1880s)	Notes re: current location (by LT)
16	Part clear, slopes to SW, few scrub oaks, stream running through	East of (and adjacent to) Saanich Rd., contains “dog-leg” of Blenkinsop Cr.
26	Bottom land, light brush	South of Ralph St. r-o-w and west of Saanich Rd., within SLNS*
28	Rather swampy (same description for 28, 39 and 40)	Adjacent to Swan L., north side (now SLNS)
29	Half under cultivation, half alder bottom	North of 28; corner of Nelthorpe and Ralph St. r-o-w
53	High, lightly wooded, slopes to E. with good view of the lake	Now contained within “clover leaf” of Pat Bay highway north-bound off-ramp to McKenzie Av.
71	Partly cleared, outlet of lake running through, slopes to S.W.; rich soil	Adjacent to and south of McKenzie Ave. (Swan Creek Park and Jolly Pl.)
72	Partly swamp, outlet of lake running through; rich soil	Between 71 and 73, Swan Creek Park
73	Partly swamp, outlet of lake running through (same descr. for 72)	South of Ralph St. (w. side of P.B. hwy), now part of Swan Creek park

** SLNS = “Swan Lake (Christmas Hill) Nature Sanctuary”*

Figure 2.2. Portion of Keen (1890) map, redrawn

2.3. Urbanisation and Watershed Development

Land clearing and cultivation was an immediate priority of European settlers, particularly after the Fraser River gold rush of 1858, which caused a sudden boom in the population (Smith, 1975). In the Victoria Official Map of 1858 (Figure 2.1), the downtown Victoria area is shown as a compact grid of streets and buildings. Outside of this area, there were only scattered cleared areas, otherwise the land cover is indicated as conifer forest, deciduous (Garry oak) forest, or riparian/wetland areas.[12] By 1862, Mayne (1862) reported, "Immediately round Victoria, and in the Saanitch [sic] district, on the peninsula... is much good land; but this is now all or nearly all settled and under cultivation." In 1860, the population of Victoria was approximately 3000 (Pemberton, 1860), and by 1864 it had doubled (Forbes, 1864). The municipality of Saanich was incorporated in 1906 (Castle, 1986).

The Canadian Northern Pacific Railway opened a small line during the First World War in 1917, connecting Victoria to the ferry at Patricia Bay; passenger service lasted only a couple of years, but freight service along the line continued until 1935 (Turner, 1997). This line passed adjacent to Swan Lake, and crossed Blenkinsop Lake on a wooden trestle; today it forms the Lochside pedestrian/bicycle trail. Railways had important effects on the landscape, and contributed to overall urban development and expansion (Turner, 1997). Furthermore, this railway also directly affected Swan Lake by taking a route through a natural ravine northeast of the lake, through which Blenkinsop Creek flowed, likely directly affecting the stream channel with partial filling of the floodplain and riparian zone.

Urban development was also accompanied by drainage “improvements” including successive lowering of the Blenkinsop Creek channel to drain the wetland and reduce flooding (e.g. Saanich Archives, 1922; Saanich Archives, 1975), and dredging and straightening of Swan Creek, beginning before 1928 (as shown in airphotos from this year, discussed below), and through the 1950s (e.g. Vernon, 1953) to 1970s (Figure 2.3).

12 Note: there is no legend for this map, however the notations (e.g. dark stars for conifers) are commonly used in other maps, and correspond with topographical features of the landscape.

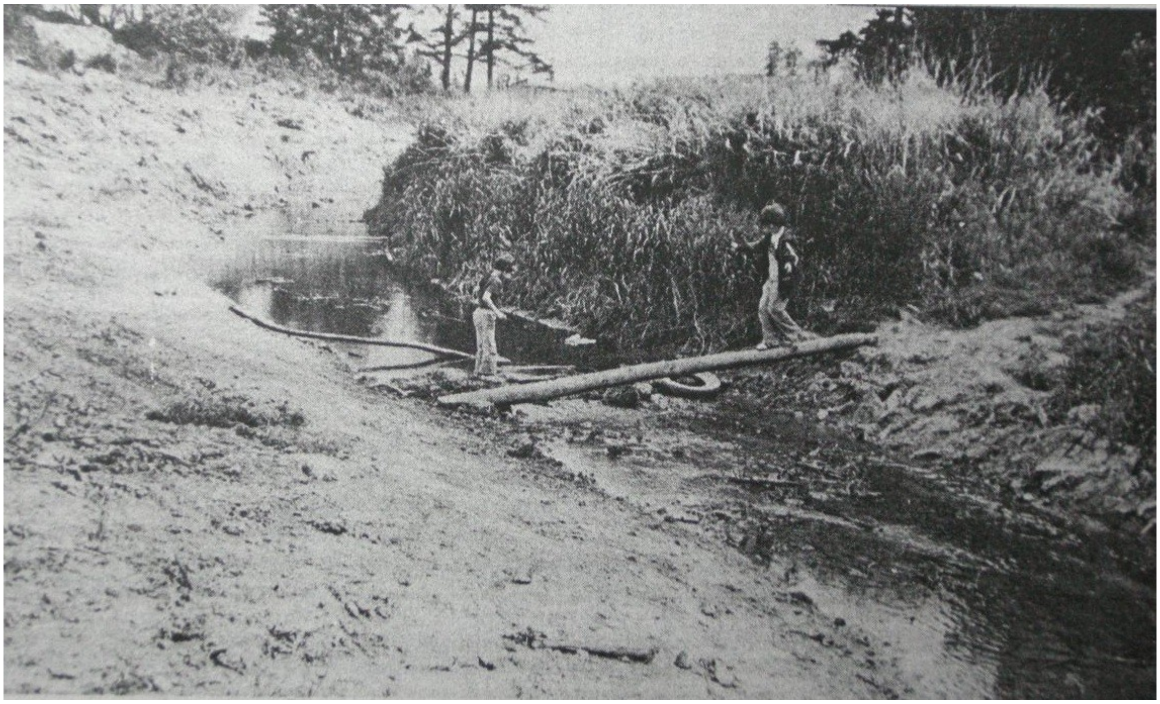

Figure 2.3. Swan Creek in 1977, showing recently stripped riparian vegetation and dredged channel (Esmond, 1977)

As the population grew, human wastes came to represent a major source of pollution. In Swan Lake watershed (as most other urban areas), initially outhouses were used for waste disposal, followed by septic fields and finally sewer systems. Rudimentary sewage treatment was implemented in small plants operated by the municipality of Saanich in the 1960s that discharged "treated" water to Blenkinsop Creek (Swan Lake Nature Centre, 1994).[13] These systems were, however, inadequate to treat the volume (Thomas, 1970; White, 1974), and were frequently overwhelmed, allowing high flows to simply bypass the system and enter Swan Lake (Swan Lake Nature Centre, 1994). Two fruit wineries operated for over 40 years near Swan Lake, and discharged wastes (fruit pulp and chemicals) into Blenkinsop Creek[14] (Swan Lake Nature Centre, 1994; Times Colonist,

13 One was located at Brett St. and another at McKenzie Ave. and Borden St., at the present site of the Public Works Yard (Zaccarelli, 1975).

14 A provincial report in 1953 estimated 3000 lbs of wastes were discharged annually by Grower's and half that amount by Victoria Winery; the waste consisted of 5-10% yeast, and 50-60% potassium tartrate (Vernon, 1953).

1995; Vernon, 1953). Local residents and municipal staff noted foul smells, and observed the creek running “red” or “black” with wastewater (Swan Lake Nature Centre, 1994), and water quality testing revealed significant nutrient enrichment from this source (e.g. White, 1974). The first documented “fish kill” occurred in 1953 (Vernon, 1953), and in subsequent years algal blooms and prolific duckweed were noted (Life, 1966; Thomas, 1970). An observation by the Municipal Engineer in 1966 (Life, 1966) suggests that the condition of the lake may have changed quite quickly:

> *The fact that the lake has changed to a severe anaerobic regime with little prior warning, combined with the length of time this state is persisting and the fact that there has only been a 10% increase both in housing and Winery production in the load of organic material being discharged to the lake, contains some suggestions that the mechanism of progressive enrichment by accumulation of nutrients from year to year may have played a part in bringing about the present situation.*

Thus it seems that the capacity of the lake to absorb wastes was previously perceived to be limitless, and the shift was seen as a surprise, typical of resilience case studies in other lakes subject to nutrient loading (e.g. Carpenter and Cottingham, 1997). By the 1970s, if not before, the lake had shifted into a turbid water state, trout were rarely seen, summer algae blooms were common, and the lake exhibited low dissolved oxygen, and a simplified plankton and macro-benthic biotic community (Zaccarelli, 1975; Morrison, 1976; McLaren, 1993; Langford, 1976). In 1974-75, sewer trunk lines were finally installed that transported sewage to open ocean disposal (Saanich Courier, 1974), and around the same time the wineries shut down (Swan Lake Nature Centre, 1994). However, as discussed below and in Chapter 5, this legacy of pollution continues to affect the lake, along with significant non-point source pollution. Although much of the waste was intercepted by the lake, there were probably also downstream effects to Colquitz Creek and Portage Inlet.[15]

In 1970, the Municipality of Saanich began to acquire land around Swan Lake for a park (Saanich Archives, 1970), and in 1975 the Swan Lake Christmas Hill Nature Sanctuary

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15 A study in 1968 estimated an annual discharge of 700 tonnes of nitrogen from Colquitz Creek into the estuarine environment (Neil *et al.*, 1968).

Society was formed under a management agreement with the municipality (Swan Lake Christmas Hill Nature Sanctuary website, no date). A number of university studies and provincial reports were drafted between 1969 and the early 1990s, assessing the extent of water quality concerns in Swan Lake.

2.4. Airphoto Interpretation

Some of the more recent patterns of development discussed above can be observed in airphotos, beginning with the earliest series available, taken in 1926/1928 (Figure 2.4). As shown in this airphoto, agriculture was widespread and most of the native vegetation had been cleared from the landscape, including the wetlands around Swan Lake and Blenkinsop Lake, with the exception of some remnants such as southwest of Swan Lake (Feature no. 7). Most agriculture consisted of annually cultivated fields, however orchards and greenhouses are also apparent in the airphoto. Blenkinsop Creek for much of its length took the form of a dug-out ditch through cleared wetlands south of Blenkinsop Lake, and connected to Swan Lake alongside the (CNR) rail grade. Grower's Winery, which would have been less than one year old in the image, is visible on Quadra St. (feature no. 5), built over top of Blenkinsop Creek. A wet meadow was still present, although apparently under cultivation, at the headwaters of the inflow stream to Swan Lake; another was located alongside the (future) Patricia Bay highway. Some sections of streams had been straightened and probably deepened, including Swan Creek, immediately downstream from Swan Lake. Other portions of the streams still had natural sinuosity, such as Swan Creek immediately upstream of the confluence with Colquitz Creek. Some remnant native terrestrial vegetation was located on Christmas Hill (Garry oak vegetation), and west of Blenkinsop Lake (conifer forest).

In airphotos from the 1960s (e.g. Figure 2.5), the effects of stream dredging and straightening and removal of riparian vegetation are apparent. Almost all native vegetation had been cleared from around Swan Lake, with the exception of a narrow fringe surrounding the lake, and a few isolated clumps of trees. The Pendray farm was operating on the east side of the lake, where various crops were cultivated and cattle were grazed in the floodplains of the lake over several decades (Zaccarelli, 1975; Swan Lake Nature Centre, 1991). Single-family residential housing had replaced agriculture in many areas. Commercial centres and the Municipal Hall were also present. An extensive network of paved roads had been constructed, including the Patricia Bay Highway running north/south on the west side of Swan Lake, and McKenzie Avenue running east/west on the north side of the lake. The winery was still in operation at this time, and sewage lines had yet to be constructed. Swan Creek, downstream of Swan Lake, had been dug out and straightened. This is especially apparent in a colour airphoto from 1966 (not shown).

Today (Figure 1.1), urban density has increased further, and two sections of Blenkinsop Creek are enclosed in culverts. Roadways have increased in number and size. Downstream of Swan Lake, Swan Creek still takes the form of a ditch that traverses through an area now used for public allotment gardens. Commercial areas have also expanded, and entail large expanses of impervious areas, especially at Quadra St. and McKenzie Ave. (NE of Swan Lake) and between Vernon Ave. and Blanshard Ave. (SW of Swan Lake). A few restoration projects have been undertaken in the watershed, including Blenkinsop Creek near Blenkinsop Lake, and Swan Creek north of McKenzie Ave. (Malmkvist, 2002). A small tributary to Blenkinsop Creek, called Leeds Creek, was restored in 1999-2001 (Edmonds, 2002). The wetlands around Swan Lake are no longer cultivated, and some native and non-native vegetation has regenerated in these areas. Trees have also grown up in many residential areas. Agriculture is still practised in the drained wetlands south of Blenkinsop Lake.

Figure 2.4. Airphoto mosaic from 1926 (upper row of images, series BA24) and 1928 (lower row, series A229); source - National Airphoto Libary

Figure 2.4a. Legend for selected features of 1928 airphoto

#	Feature
1	Blenkinsop Lake, showing railway trestle bisecting the lake north/south
2	North-flowing inflow stream to Blenkinsop L.
3	South-flowing outflow channel (dug ditch) through cleared wetland south of Blenkinsop L.
4	Wet meadow, previous headwaters of Swan Lake
5	Newly constructed winery on Quadra St.
6	Leeds Creek, tributary inflow to Swan Lake
7	Swan Lake
8	Remnant natural wetland (shrubs)
9	Channelized outflow stream from Swan Lake (Swan Creek)
10	Tributary to Swan Creek
11	Panama Flats, cleared wetland and ditches along Colquitz Creek
12	Lower Colquitz Creek, downstream from confluence with Swan Creek
13	wetland along (future) Pat Bay highway
14	Christmas Hill
15	Gabo Creek (outflow of Rithet's Bog, flows to Colquitz)

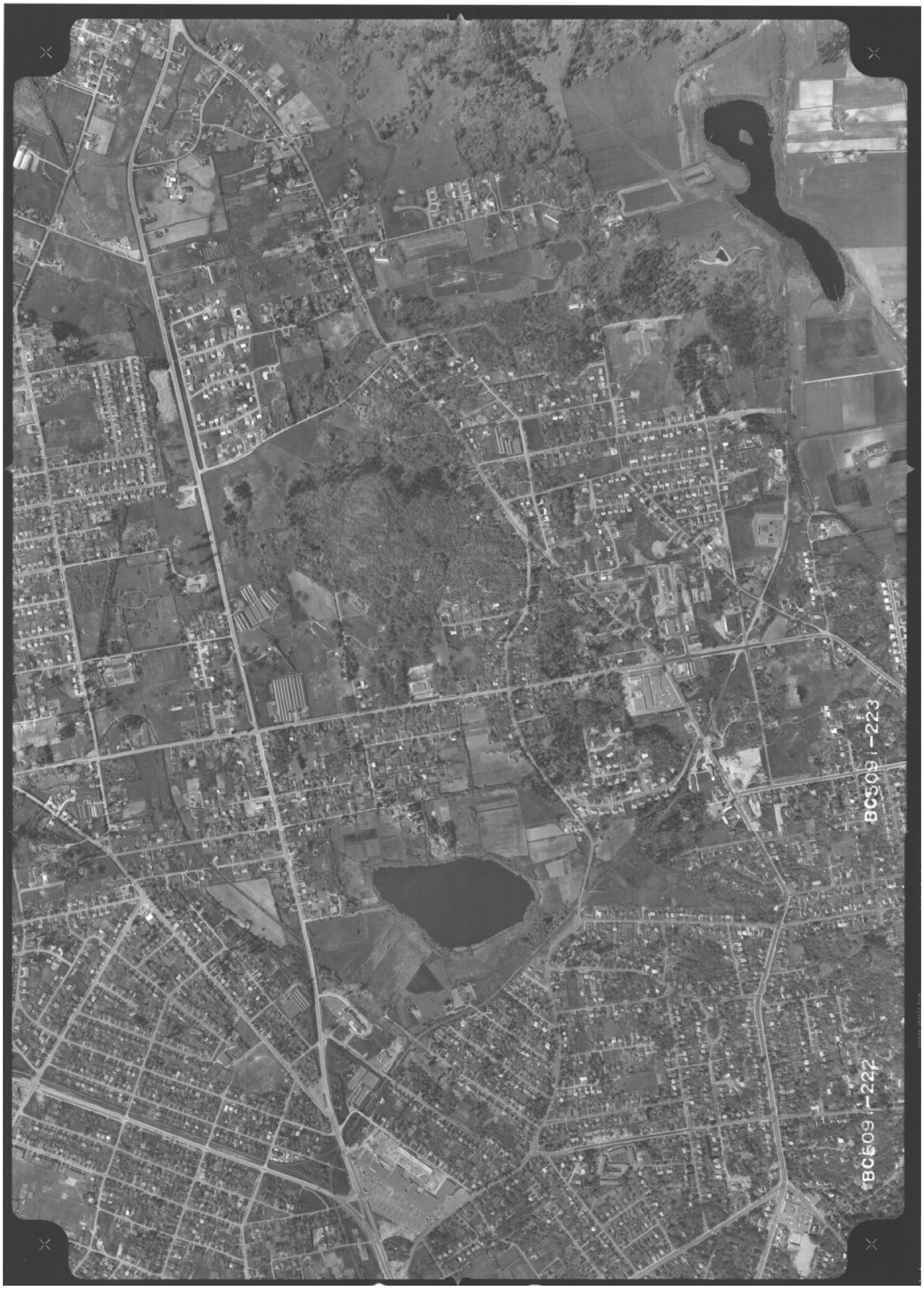

Figure 2.5. Airphoto from 1964 (BC5091_222 & 223); source, Provincial Airphoto Warehouse

2.5. Discussion

Some of the most important events, as related to the watershed processes, are summarised in the timeline below (Table 2.3). Events have been grouped in “phases,” as follows. These are not well-defined periods, and probably overlapped more than indicated here, however they are useful for clarification.

1. Post-contact (and inferences of earlier times). Prior to European arrival, indigenous people influenced landscape-scale processes with activities such as prescribed burning, harvesting and cultivating plants and fishing/hunting. The reef net is highlighted as a particularly important cultural and resource procurement activity that may have influenced wetland vegetation structure and function (see also Appendix C). Cultivation practices may have enhanced ecological resilience by creating a 'mosaic' effect in the vegetation community (Turner *et al.,* 2003; Anderson, 1999); historical anecdotes and archaeological evidence tell of abundant wildlife and plant resources, despite a large indigenous population. The hydrological effects of prescribed burning and maintaining a more open tree canopy are less well characterised, as discussed in Chapter 6. Contact with Europeans had an enormous effect on indigenous practices and cultures. Consequences discussed here include mortality from disease, loss of cultural practices and access to traditional lands and cessation of resource management activities. This may have had subtle effects on ecosystem structure and function, even before the direct effects of European land management were implemented.

2. Land clearing and agriculture (1843 to ca. 1880s). Beginning in 1843, European settlers carried out large-scale land clearing for food cultivation and harvesting timber for wood fuel. Agriculture as practised by the settlers required draining wetlands, ploughing soils and removing most of the native vegetation. Thus began a cycle of soil erosion and nutrient mobilisation into downstream systems, including Swan Lake. Ecosystems were generally viewed as value-less “waste” land, until converted to highly managed systems. For example as stated by surveyor J.D. Pemberton (1860, p.23), “Marsh lands are usually easily drained, and reclaimed by burning them up in summer; these lands afterwards produce the best crops.” This phase extended into the late 1800s, at which time Victoria took on characteristics of a small city, and population increase after the gold rush necessitated a shift to a focus on urban infrastructure and housing.

3. Early infrastructure and residential development (ca. 1880s to 1940s). Beginning in the late 1800s and early 1900s, development of infrastructure such as roads, railways and residential areas characterised land use in the watershed. By this time, most of the land in Swan Lake watershed, and Victoria in general, had been cleared of native vegetation. The McKenzie property was subdivided into 5-acre lots in 1884, and by 1928, most of the land had been cleared. The beginning of a road grid is evident in a 1928 airphoto (Figure 2.4). The operation of the wineries was a critical event during this phase, due to the enormous volume of organic waste that was discharged into Swan Lake. Before pollution became more serious, there are accounts of outdoor recreation such as fishing and swimming in local areas including Swan Lake. Understanding of the effects of sewage pollution and other ecological effects of human activities was evidently quite low (judging by behaviour and a lack of anecdotes to the contrary), until the results became impossible to ignore, and human health was put at risk. As early as 1905, sewage pollution in Portage Inlet and the Gorge was noticed to be a “nuisance” (The Daily Colonist, May 17, 1905, cited in Langford, 1974), however this problem was not addressed in a comprehensive manner until much later.

4. Post-war industrialisation and mechanisation (1940s to late 1960s). An increasing population and economic development, particularly after the Second World War, led to expansion of urban and suburban areas, which in this timeline continued into the early 1970s. This was facilitated by technological innovations, such as the personal automobile, cheap oil, and chemicals (e.g. for fertilisers that increased crop yields). The “baby boom” led to an expansion of residential housing into areas that were previously used for farming. Roadways were expanded, necessitating more culverts and increasing impervious surfaces in the watershed. This increased surface flows and contributed to more flooding and channel erosion. Many streams during this time became severely degraded due to pollution, channelization to convey flows, invasive species, and erosion due to high-energy runoff (and removal of floodplains and other natural channel features to dissipate this energy). This degradation in turn led to some streams being enclosed in storm drains (Neate, 1967), for example Bowker Creek and small tributaries in the Swan Lake watershed, as well as portions of Blenkinsop Creek under McKenzie Ave. and Quadra St. Toward the end of this phase, many people began to realize the loss of functional ecosystems also entailed a social loss.

5. Urban-ecosystem conflict (late 1960s to Present). This phase still characterises patterns of development in the watershed. On one hand the emerging environmental movement of the late 1960s, in large part mobilised by Rachel Carson's (1962) book "Silent Spring," helped to spread awareness about pollution and other human impacts on ecosystems. Frank Neate, a municipal engineer with Saanich, released a report in 1967 outlining a bold vision for restoring Colquitz Creek as a healthy ecosystem of value for residents and wildlife, and outlined principles for ecological design based on "clustered" development (which resembles today's "Smart Growth"). Such planning ideas were influenced by Ian McHarg's (1969) now-iconic book "Design With Nature." This vision led Saanich to acquire property along the creek to maintain it as an open waterway and allow for stream restoration, although development patterns did not follow Neate's recommendations. The vision extended to Swan Creek and Swan Lake, and property was acquired around Swan Lake; in 1975, the Nature Sanctuary was formed. Other proposals for restoration were drafted in this time (e.g. Van Stolk, 1977). Many university and consultants' reports were conducted in the late 1960s and early 1970s that drew attention to degraded conditions in Colquitz Creek and Swan Lake and its streams (Neil *et al.*, 1968; Thomas, 1970; Langford, 1974; Shepard, 1975), and newspaper stories expressed public anger about that state of the environment (e.g. Esmonde, 1977). However, on the other hand, economic development rapidly increased in this time, and for a variety of reasons that remain unclear, various restoration initiatives related to the watershed that were begun in this phase were abandoned. Many parks exist, but most streams, lakes and wetlands remain in a degraded state. As the watershed has become increasingly urbanised, few people remain who recall fishing in the local streams like Colquitz Creek, and many are unaware that Blenkinsop Creek, for example, exists at all. Several restoration projects were carried out in the late 1990s and early 2000's to improve the function of sections of Blenkinsop, Swan and Leeds Creek (Malmkvist, 2002; Edmonds, 2002); these were site-specific projects initiated by private companies, rather than municipal initiatives.

Table 2.3. Historical timeline, with critical ecological events highlighted

"Phase"	Date	Description	Reference
Post-contact	1774	First contact between Europeans (Spanish) and native people (Nuu-chah-nulth) in coastal BC, Yoquot ("Friendly Cove"), Nootka Island	Archer, 1978
	1790s to 1800s	Changes in indigenous cultures and populations due to introduced goods, fur trade, disease.	Boyd, 1999a (re: disease)
Land Clearing and Agriculture	Spring, 1843	Fort Victoria constructed	Bowsfield, 1979
	1850-1852	"Douglas treaties" signed by James Douglas with Songhees, Saanich peoples, acquiring their lands in return for payment and guarantee of access for hunting/fishing	Keddie, 2003
	May 18, 1857	Kenneth McKenzie (HBC employee) purchases Section 64, including Christmas Hill and the north half of Swan Lake; resides there until his death in 1874.	Saanich Archives land records; Nesbitt, 1948; Sampson, 1973
	1858	Fraser River gold rush; commercial boom in Victoria; Victoria Official Map produced	Smith, 1975; Victoria Official Map, 1858
	1873	Elk Lake water works completed (including pipeline supplying drinking water to Victoria crossing Swan Lake outflow stream)	British Daily Colonist, Oct. 7, 1873
	ca. 187?	Blenkinsop wetland cleared, likely drained with ditches connecting to inflow to Swan Lake	Maps from 1861 and 1888
Early infrastructure (roads, res. subdivision)	1884	Subdivision of Lake Hill (McKenzie property), into 5 acre lots, advertised for sale in local paper	Swan Lake Nature Centre, 1994
	1906	Municipality of Saanich incorporated, Blenkinsop Rd. constructed	Green and Castle, 2005
	Apr. 29, 1917	Canadian Northern Pacific Railway line opened between Victoria & Patricia Bay; route located adjacent to Swan Lake, across trestle on Blenkinsop Lake.	Turner, 1997
	1918	Thomas Pendray purchases land adjacent to Swan Lake for a dairy, various crops grown in wetlands; up to 45 head cattle kept, into 1970s	Saanich Archives, 1970; Swan Lake Nature Centre, 1991
	1927	Grower's Wine Co. (formed 1923) opens winery on Quadra @ Reynolds; wastes discharged into Blenkinsop Creek until 1970s	Kersey, 1976; Swan Lake Nature Centre, 1994
	before 1928	road across Swan Lake outflow stream contructed (future Douglas St.)	1928 airphotos (show dirt road here)
	1920s to 1940s	Gradual increase in population, expansion of urban areas; street-car system	

Table 2.3 continued

Post-war industrialisation	1945-1948	World War II - post-war effects include population and economic boom, increased motorized transport, increase in fertiliser/pesticide	
	1953	First record of summer "fish kill" and low oxygen conditions in Swan Lake	Vernon, 1953
	1960	Patricia Bay Highway (#17) opened, expanded roadway (Douglas St.) across outflow stream of Swan L.	Wikipedia, no date
Conflict: expanding infrastructure; value placed on natural areas	1967	F.E. Neate (Municipal Engineer) releases plan for protecting and restoring Colquitz Creek and tributaries	Neate, 1967
	1970	Saanich purchases Pendray property, approved by referendum of ratepayers in 1967 (first land acquisition around Swan Lake)	Saanich Archives, 1970
	1974	Saanich Council approves Department of Agriculture proposal to establish allotment gardens, recommends property along Swan Creek downstream of Patricia Bay highway	Saanich Archives, 1974a
	1974	Saanich Municipal Works completes sewer lines servicing much of municipality, ending flows of sewage and winery wastes into lake; wineries close soon afterward	Saanich Courier, 1974a; Swan Lake Nature Centre, 1994
	1975	Swan Lake Christmas Hill Nature Sanctuary Society formed, with management mandate for Swan Lake and wetlands and Christmas Hill	Swan Lake Christmas Hill Nature Sanctuary website, no date
	1975	flooding concerns in Blenkinsop Creek due to channelization	Saanich Archives, 1975
	1976	Re-design of Swan Creek proposed by Swan Lake Christmas Hill Nature Centre, to increase sinuosity and reduce steepness of banks	Morrison, 1976
	1979	Mowing ceases in Swan Lake wetlands	Morrison, pers. comm.
	1995	Lochside Trail (connector to Galloping Goose) constructed on old CNR line	Green and Castle, 2005
	1999-2002	Stream and wetland restoration in several small sites: upper Blenkinsop Creek; Swan Creek north of McKenzie; Leeds Creek	Malmkvist, 2002; Edmonds, 2002

2.6. Conclusion

Events over a relatively short period of time, roughly 150 years, caused a number of significant changes to the landscape. These changes are mostly related to alterations of water flows and nutrient cycling. The pre-contact landscape was vegetated with a multi-storied mosaic of conifer/deciduous forests and wetlands, with most wetlands dominated by woody species. Thus the native ecosystems functioned to minimize surface runoff, and maximize evapotranspiration, retention and filtration of surface water, and groundwater recharge (in certain areas). Abundant vegetation was key in cycling water through biotic pathways, thus maximizing solar energy dissipation (Ripl, 2003). Nutrients were for the most part retained and recycled, and soils were rarely disturbed, with only periodic pulses of enrichment from the land to aquatic ecosystems. These processes are important for ecological health and resilience, as described in the following chapters.

First Nations burning and cultivation introduced a managed disturbance that may have improved ecological resilience by enabling smaller scale "release" of bound nutrients (e.g. fuel in the form of forest litter; older wood in the case of willow thickets) and maintaining multiple age classes that were more resilient to disturbances such as pest outbreaks (Turner *et al.,* 2003). Collectively, these attributes enabled persistence of the existing structure and function of the ecosystems in the watershed. Reconstructing indigenous peoples' influence on landscape processes in the past is an important but difficult part of establishing reference conditions, in order to properly evaluate changes in modern times. In a landscape such as Swan Lake watershed and the surrounding region, where ecosystems co-evolved with people due to management strategies (e.g. landscape burning), it is important to understand these interactions, since without people, the watershed may well have had different attributes.

Changes with European settlement and development included restrictions of First Nations' access to land and resources, deforestation for wood fuel and agriculture, drainage of wetlands and stream channelization. Vegetation clearing initiated a cascade of consequences, ultimately leading to soil and nutrient loss from the land, eutrophication of fresh and marine waters, and reduced ability of ecosystems to provide "ecosystem services" for human inhabitants. Streams and wetlands, considered valuable resources to First Nations, were cleared and transformed to one-way drainage systems to enable industrial land management. Knowledge about ecological processes has greatly increased in the past 30 years, but this has merely enabled better understanding of the scope of the problem, with little concerted effort to resolving them at the scale of the landscape or watershed. A more detailed assessment of current watershed processes is provided in the following chapters, while patterns of change, as they relate to ecosystem resilience, are further analysed in the discussion in Chapter 6.

In terms of ecological resilience, throughout the history of European development, little planning or deliberate management appears to have been devoted to maintaining healthy or resilient ecosystems within the watershed. Instead, human social-economic objectives predominated. This has led to a number of consequences for human well-being that are examined in more detail in the following chapters.

Chapter 3. Proper Functioning Condition of Main Stream Channels in Swan Lake Watershed

Streams, wetlands and riparian ecosystems perform a number of functions important for resilience, such as providing habitat (thus enhancing biodiversity), processing nutrients, and regulating (surface and ground-) water flows of importance to a wide variety of species and communities (Naiman and Bilby, 2001; Mitsch and Gosselink, 1986; Prichard, 1998). Due to their position in the landscape, streams integrate watershed-scale processes, and can be examined as one indicator of watershed health (e.g. Booth *et al.*, 2002; Morley and Karr, 2002). Typically, river management reduces natural variability, for example through channel straightening and "cleaning," reduction of floodplains, and channel armouring to reduce lateral movement (Booth *et al.*, 2004; May *et al.*, 1997). This management paradigm is now recognised to lead to degraded ecological conditions that in many cases exacerbate management concerns in the long term and decrease ecological resilience (Jungwirth *et al.*, 2002; Holling and Meffe, 1996). Consequently, there is a need for developing and refining criteria for and indicators of ecological riverine health (Palmer *et al.*, 2005; Jungwirth *et al.*, 2002).

Stream assessment and restoration have been undertaken using a wide variety of approaches and techniques, yet there is often a high rate of failure to improve habitat and stream ecosystems (e.g. Palmer *et al.*, 2005; Walsh *et al.*, 2005). Part of the problem is a failure to understand fundamental principles of watershed-scale hydrology and geomorphology that control stream channel responses to disturbance; instead, projects are often focused at the reach or site scale where inappropriate structures are installed that are unable to withstand larger scale disturbances such as flashy flows (e.g. Shields *et al.,* 2005; Walsh *et al.*, 2005). Since there has been excessive focus on channel *stability* in the past, at the expense of the range of variability of natural biotic and abiotic processes, incorporating resilience theory provides a means to shift the focus from equilibrium-based "states" to dynamic "processes" and a view of streams as dynamic and open systems.

In order to better characterise the effects of past and ongoing management of stream channels and associated ecosystems in Swan Lake watershed, a "Proper Functioning Condition" assessment was carried out. As discussed in Chapter 1, Proper Functioning Condition is a methodology developed by the U.S. Bureau of Land Management and associated agencies for assessing stream "health." It is used extensively in the U.S.A. for evaluating the basic physical conditions of streams, particularly those susceptible to degradation from grazing and logging. Physical properties are recognised as critical to stream health (Maddock, 1999). PFC methodology (PFC-M)[1] is less commonly used in Canada and has rarely been applied to urban systems, however over the past ten years Aqua-Tex Scientific Consulting Ltd. has applied it in these situations, and I have worked with them on a number of professional urban and rural stream assessments using this system. PFC-M has also been used as design criteria for urban stream restoration (Edmonds, 2002; Malmkvist, 2002). Although the assessment procedure is qualitative, it is based on a body of quantitative research in the areas of geomorphology, hydrology and vegetation, and quantitative measurements may be undertaken in the field to support the evaluation (Prichard, 1998; Rosgen, 1994).

The literature forming the basis of PFC-M acknowledges the dynamic nature of streams, and emphasises energy dissipation as a prime function in healthy systems (USDI, 1993). As such, it has much in common with resilience theory; a "properly functioning" stream can absorb disturbances without undergoing severe degradation (i.e. shifting to an alternative stable state). However, to date PFC-M has not been linked with the body of research surrounding resilience. Furthermore, PFC-M incorporates a linear view of succession, which as discussed in Chapter 1 may be simplistic in the case of complex systems. If this contradiction can be reconciled, PFC-M may represent a metric for assessing watershed resilience, at least at the scale of the stream channel and lake shoreline.

The hypothesis tested in this part of the study was: *PFC-M entails a process that can be used to evaluate ecological resilience (in terms of physical structure) of urban stream*

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1 The acronym "PFC-M" is used here in order to avoid confusion with the term "proper functioning condition" (PFC) which indicates a state of a riparian/wetland system.

channels.

The objectives were therefore to:

1) Assess the main-stem streams of Swan Lake watershed, i.e. Swan Creek and Blenkinsop Creek, according to Proper Functioning Condition methodology, and summarise measures needed to improve function where needed, according to the method's principles.

2) Evaluate the utility of Proper Functioning Condition methodology for characterising urban streams and as a potential tool for assessing ecological resilience.

3.1. Theory and Methods

Proper Functioning Condition methodology was originally designed to address the widespread degradation of stream channels and wetlands observed in mid-western rangelands due to inappropriate grazing practices and other forms of land management (USDI, 1993). PFC-M entails a process (outlined below) and a field assessment by an interdisciplinary team, to determine if the physical attributes of a stream/wetland are sufficient to maintain the system in an equilibrium with the landscape setting, given the water and sediment regime. The attributes are grouped under the headings of Hydrology, Vegetation, and Soils (i.e. erosion/deposition). Based on the assessment, the stream or wetland is given a rating of "proper functioning condition" (PFC), "nonfunctional" (NF) or "functional at risk" (FAR). For FAR, where possible an upward or downward trend is indicated. PFC-M provides a framework for characterising a stream or wetland, and for outlining restoration priorities and options. The definition of PFC reads as follows (USDI, 1993).

> ***Riparian-wetland areas are functioning properly*** *when adequate vegetation, landform, or large woody debris is present to dissipate stream energy associated with high waterflows, thereby reducing erosion and improving water quality; filter sediment, capture bedload, and aid floodplain development; improve flood-water retention and ground-water recharge; develop root masses that stabilize streambanks against cutting action; develop diverse ponding and*

> *channel characteristics to provide the habitat and the water depth, duration, and temperature necessary for fish production, waterfowl breeding, and other uses; and support greater biodiversity. The functioning condition of riparian-wetland areas is a result of interaction among geology, soil, water, and vegetation.*

Furthermore, a rating of PFC indicates there is sufficient structural integrity in order to withstand physical disturbance in terms of a dynamic equilibrium and adjustment of channel shape and form (USDI, 1993).

In contrast, *functional-at-risk* refers to "riparian-wetland areas that are in functional condition, but an existing soil, water, or vegetation attribute makes them susceptible to degradation." *Nonfunctional* refers to "riparian-wetland areas that clearly are not providing adequate vegetation, landform, or large woody debris to dissipate stream energy associated with high flows, and thus are not reducing erosion, improving water quality, etc., as listed above." (USDI, 1993).

In order to carry out a PFC assessment, the interdisciplinary team must carefully analyse the definition of PFC to determine if the attributes and processes of a healthy stream are present, using a checklist, as compared to the *capability* and *potential* of the system[2]; a management plan is then developed based on this assessment (USDI, 1993).

Note that PFC-M evaluates the *minimum criteria* necessary for supporting healthy streams and wetlands, and although the focus is on physical elements and processes, it does not preclude detailed biological study (e.g. bioassessment and species inventories) which can be used for additional information (Prichard, 1998). By focusing on geomorphic and biophysical processes, the fundamental requirements of riparian/wetland areas can be addressed, allowing "values" such as recreation, fisheries and grazing to be derived therefrom (Prichard, 1998). Furthermore, while biological indices must be locally derived based on detailed knowledge of community structure and valid comparison with "pristine" areas (e.g. Townsend and Riley, 1999), PFC-M is a framework that can be applied to virtually any lotic (or lentic) ecosystem (P. Lucey, pers.

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2 The definitions of these terms are given in Appendix B, and are determined using historic photographs, present/historic species lists, soils assessments, watershed condition and landform, and considering "limiting factors." In some cases, an Ecological Site Inventory is necessary to make this determination.

comm.). It provides a well documented process to assess physical attributes and a rationale for restoration and management (e.g. Newman and Swanson, 2008).

A complementary methodology frequently used for PFC assessments is the Rosgen (1994, 1996) system of stream channel classification. This system is based on geomorphology and consists of a multi-level classification of physical channel characteristics based on their landscape position (topography and valley form), and channel attributes such as sinuosity, width-depth ratio, entrenchment ratio, etc. This system provides a useful process for determining the "expected" channel type given the topography and climate, and the likely channel evolution with disturbance as well as restoration guidelines (Rosgen, 1996). A multi-level classification is used, with 41 possible channel types, grouped under seven general categories; for example, "A" channels are steep headwater streams that lack floodplains and are low in sinuousity, while "C" channels have greater sinuosity, accessible floodplains and exhibit point-bars due to sediment deposition (Rosgen 1994). This system is widely used, in particular by American federal agencies as well as non-profit groups and private consultants, despite criticism by some (Malakoff, 2004; Simon *et al.,* 2007; Kondolf, 2006)[3].

Methods

As a part of an assessment of the Colquitz watershed completed for the Municipality of Saanich, Swan Creek, Swan Lake and Blenkinsop Creek and Blenkinsop Lake were evaluated according to the PFC criteria, by the author and other associates of Aqua-Tex Scientific Consulting Ltd., who had backgrounds in vegetation ecology, aquatic biology and hydrology, and were experienced in assessing urban streams. Since the team was much more familiar with the lotic PFC methods (moreso than the lentic/wetland version), the stream channels assessment is the main topic of discussion here. Background

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3 Criticisms include: a reliance on "out-dated" theories of fluvial geomorphology; a lack of documentation for asserted hydraulic relationships and formulae; over-reliance on site conditions and equilibrium without due regard for larger-scale dynamic processes and landscape history; a "preference" for single-thread channels even where not supported by historical evidence or sediment transport regimes. However many of these criticisms appear to have valid counter-arguments, and a full review of conflicting opinions is beyond the scope of this text.

information regarding land use and history was provided mainly by L. Townsend (see preceding chapters), and through other research conducted by Aqua-Tex Scientific Consulting over previous years.

In the field, the team walked the length of Swan Creek, from the confluence with Colquitz Creek to Swan Lake, around part of Swan Lake, and proceeded upstream along Blenkinsop Creek, to Blenkinsop Lake. Reaches were designated in the field based on common hydrological and geological characteristics and delineated with a hand-held GPS (Garmin GPSMap 60CSx). For each reach, observations were recorded regarding vegetation species, Rosgen channel type and channel substrate, concerns such as erosion/deposition, and land use. The PFC criteria were assessed in the field according to the checklist, and discussion points were noted. A summary report with restoration and management recommendations was prepared for the municipality of Saanich (Buchanan *et al.*, 2008). Findings relating to Swan Lake watershed are summarised here and in Buchanan *et al.* (2008), and additional discussion is provided.[4]

In December 2008 and January 2009, two reaches were re-assessed, after I identified some factors inconsistent with the prescribed methods and initiated discussions with the group. This involved discussions about the practice of applying PFC-M to urban systems in general, and a field visit to the two reaches (Swan Creek, Reach 5 and Reach 1 of Blenkinsop Creek).

3.2. Assessment Findings

The reach breaks are shown in Figure 3.1 and Figure 3.2. Swan Creek was stratified into eight lotic reaches (Swan Lake constitutes Reach 9); five lotic reaches were designated in Blenkinsop Creek, with Blenkinsop Lake as Reach 6.

According to the field assessment, approximately 35% of the linear length of Swan Creek was rated as *properly functioning*, 15% as *functional at risk*, and 50% as *nonfunctional* (Figure 3.2; Figures 5.3-5.7). In Blenkinsop Creek, 23% was rated as

4 Vegetation species are not listed except where they are of particular interest. Note that only the main-steam channels of Swan Creek and Blenkinsop Creek were assessed; there are additional tributary channels in the watershed (see Chapter 1) that were not included in this study.

properly functioning, 66% as *nonfunctional*, and 11% as *functional-at-risk*. The main reasons for nonfunctional and functional-at-risk ratings were enclosure in pipes, previous channel excavation and straightening, resulting in lowered water table and lost floodplain access, combined with erosive flows, sparse riparian vegetation and active erosion. Almost one quarter (626m) of the length of Blenkinsop Creek is enclosed in culverts. Trampling and invasive species are also concerns in many areas.

Table 3.1. Reach summary for Swan Creek and Blenkinsop Creek

Swan Creek				
Reach #	Length of reach (m)	Condition (rating)*	Rosgen Channel	Concerns
1	61	PFC	C4	(minor) invasive species
2	490	NF	Gc6	degraded channel form; erosion; trampling; invasive species
3	54	PFC		reed canarygrass choking channel
4	420	PFC	C6	isolated trampling; invasive species
5	361	FAR(=)	Bc6	lack of riparian veg and large wood, channel complexity
6	292	PFC	C6	isolated trampling; invasive species
7	367	NF	G6	degraded channel form; invasive species; lack of floodplain and riparian vegetation
8	353	NF	ditch	lack of riparian veg.; incompatible land use (community gardens)
9	n/a	PFC	n/a (Lake)	eutrophic conditions; water quality, invasive species
Blenkinsop Creek				
1	296	NF	ditch	incised channel; bare banks; lack of floodplain and wood/rock in channel
2	249	FAR(-)	B2	active erosion; invasive species
3	154	NF or N/A	n/a	enclosed in a culvert
	168	N/A	n/a	enclosed in a culvert (not assessed or counted)
4	1073	NF	ditch	no floodplain or other channel features; sparse riparian vegetation; invasive species; garbage; 626m enclosed in culverts
5	517	PFC	C6	some invasive species near Lochside trail
6	n/a	PFC	n/a (Lake)	Eutrophic conditions; bullfrogs; poor water quality

** for functional at risk, + indicates an upward trend; - indicates a downward trend; = indicates no apparent trend*

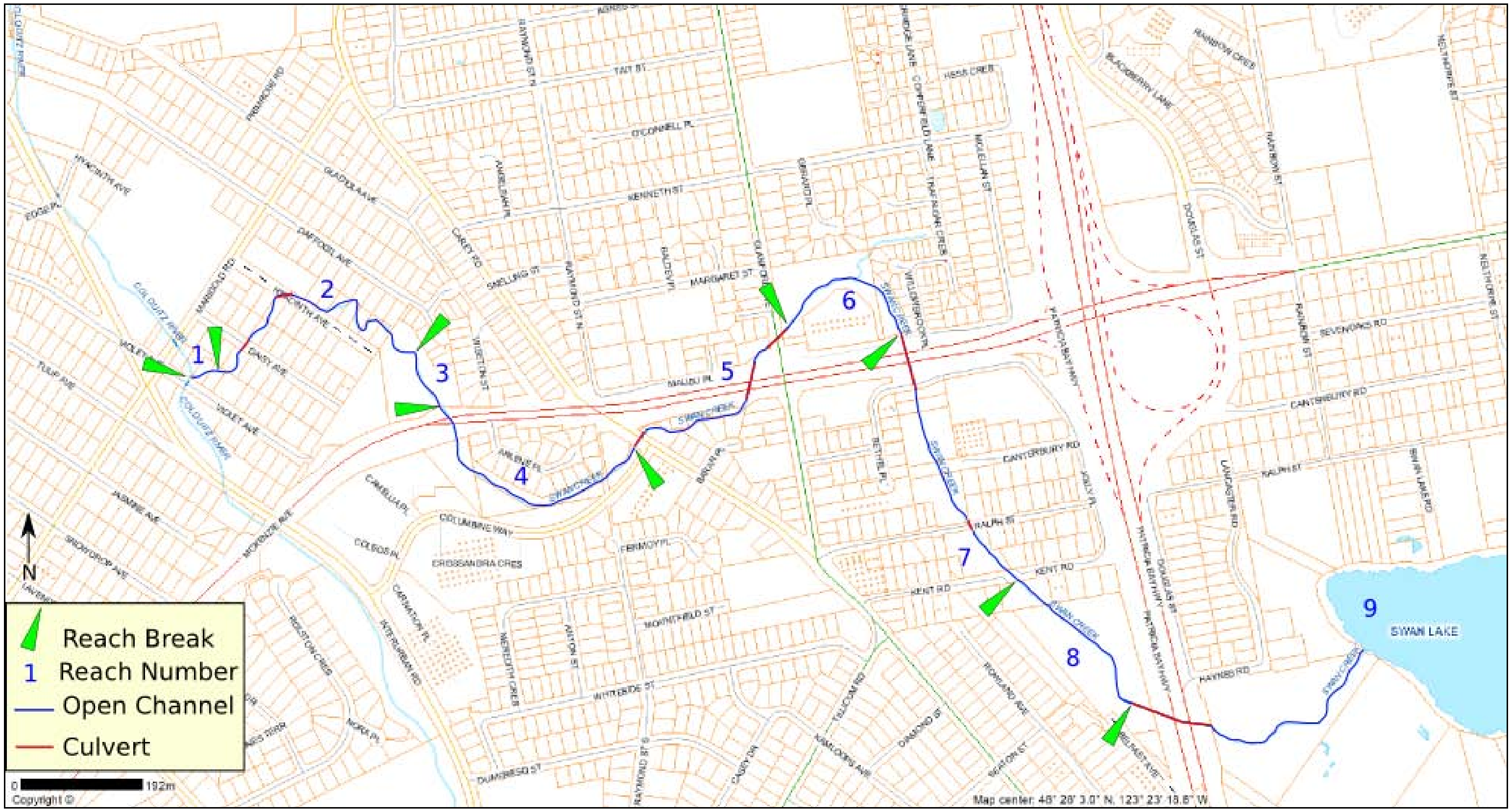

Figure 3.1. Swan Creek reach breaks (image source: Saanich public GIS viewer)

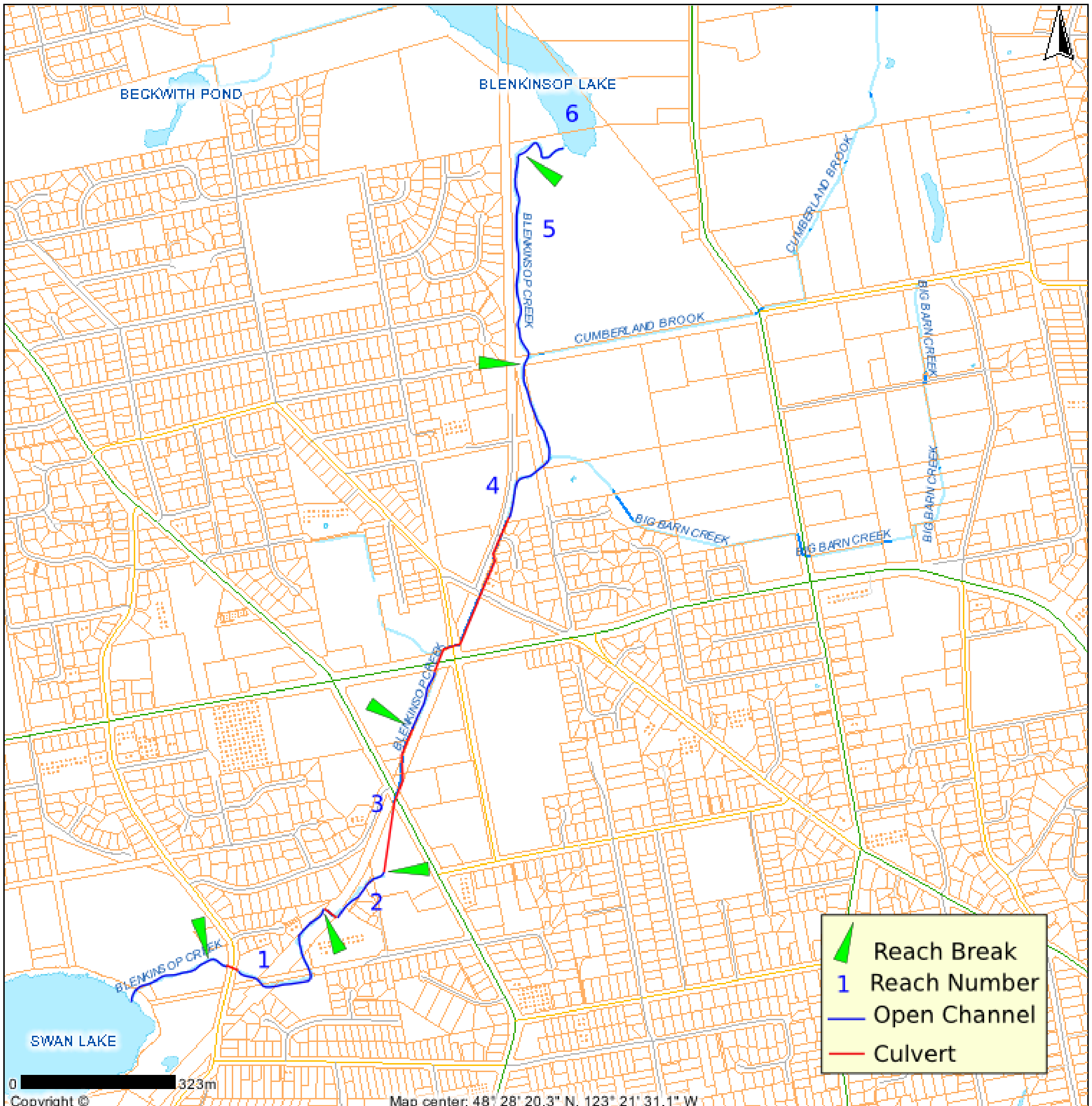

Figure 3.2: Blenkinsop Creek reach breaks (image source: Saanich public GIS viewer; note scale is smaller than in Figure 3.1)

3.3. Discussion

The physical condition of stream channels influences their ability to absorb disturbances, such as high-energy flows and pulses of nutrients, sediment and pollution (Maddock, 1999; Prichard, 1998). Degraded streams fail to perform the functions listed in the definition of PFC, and serve more as pipes that transfer and propagate disturbances to downstream areas. In the latter scenario, the watershed becomes over-connected, with little energy dissipation, i.e. is less resilient to disturbances such as extreme rainfall events and pollution. Stream channels are also a product of watershed scale pattern and process, such as vegetation cover and land use and can therefore provide some indication of terrestrial ecological resilience (e.g. Alberti, 2005). For example, loss of native forests and impervious areas can result in degraded channels, even at low levels (e.g. <10% total impervious area) (Booth *et al.,* 2002). Conversely, native vegetated landscapes, wetlands and riparian zones help to buffer gradients in temperature and disturbance, creating a more hospitable environment for a wide range of species and limiting loss of soil nutrients (Pokorný, 2001; Ripl, 2003).

Stream Channel Conditions

A large proportion of the assessed stream channels are degraded (Table 3.1). As shown in Chapter 2, some of this degradation is due to previous channelization (dredging) carried out by the municipality and private landowners, to more “efficiently” convey water off the land and to allow development and farming within floodplains. In fact, the entire channel length was probably excavated at various times in the past.[5] Impervious surfaces in the watershed contribute to ongoing erosion by creating high-energy surges of water during rain events that prevent re-establishment of floodplains and riparian vegetation (Walsh *et al.*, 2005; Chapter 5). Culverts also contribute greatly to poor conditions by concentrating flows and exacerbating erosion (McBride and Booth, 2005; Avolio, 2003); Swan Creek passes through seven culverts out of a total 11 road crossings (the rest of which are spanned by bridges), over a total stream length of less than 3 km. Blenkinsop

5 For example, airphotos from the 1960's clearly show active channelization throughout the watershed (see Chapter 2).

Creek is approximately 2.5 km long and approximately 626m is enclosed in culverts through a commercial area, plus five culverts at road crossings. Furthermore, water quality was suspected of being poor, given hydrocarbon odours noted and the proximity of roads; this suspicion was confirmed with chemical analysis discussed in Chapter 5.

The ecological costs of these conditions include:

- Accelerated in-stream erosion, with sediment and associated nutrients transported into Swan Lake and Colquitz Creek (visual observation confirmed active erosion; sedimentation is quantified in Chapter 5);
- Little filtration or opportunity for biological processing of nutrients and pollutants, due to simplified channel conditions, separation of the channel from its floodplain due to incision and frequent high flows (e.g. Cadenasso *et al.,* 2008);
- Loss of fish habitat for anadromous and resident salmonids (salmon and cutthroat trout) due to erosive flows and direct channel modification (channel complexity and large wood were lacking throughout most reaches);
- Loss of riparian vegetation and associated habitat for aquatic and terrestrial wildlife due to direct removal, erosive flows and dominance by invasive species, as confirmed with visual observations.

Social/economic values may also be influenced by stream condition. For example, the restored area within the Willowbrook subdivision (Reach 6 of Swan Creek; Malmkvist, 2002), is highly appreciated by the local neighbourhood as a walking and wildlife viewing area (Barraclough and Hegg, In Press). Another restoration site in Reach 5 of Blenkinsop Creek provides natural pest control to the adjacent farmer's field, in the form of increased pest predation by birds nesting/perching in the planted riparian vegetation, a service estimated to be worth $35,000 per year in deferred pesticide costs (Barraclough and Hegg, In Press). Both these sites were rated as “properly functioning,” and contribute to watershed resilience by slowing flows (thus preventing erosion), processing nutrients (preventing downstream eutrophication) and retaining water for more effective evapotranspiration (and dissipatation of solar energy), functions important to watershed resilience. Unfortunately, they constitute relatively small portions of the total linear length of the assessed streams.

Despite the high percentage of the stream channels that were rated as "nonfunctional," there are nevertheless many opportunities for stream channel rehabilitation, as summarised in Table 3.2.

Table 3.2. Summary of restoration recommendations, based on PFC assessment

Stream (Reach #)	Recommendations	Relative cost/effort
Swan (2)	Re-grade bank; create floodplains, increase channel complexity; riparian plantings	High
Swan (3)	Mulch/plant with willow and other fast-growing deciduous species to replace reed canarygrass (see Appendix D)	Low
Swan (4)	Riparian plantings and community education/signage	Low
Swan (5)	Soil bioengineering (with live willow stakes); riparian plantings; increase channel complexity	Moderate
Swan (5,6)	Control invasive species and native plantings	Low
Swan (7,8)	Create wetland and channel complex (see text)	High
Blenkinsop (1)	Create wetland and channel complex (see text)	Moderate
Blenkinsop (2)	Stabilize eroding areas	Low
Blenkinsop (3)	Daylighting (along with re-development of commercial areas)	High
Blenkinsop (4)	Floodplain terracing; increased channel complexity (e.g. rock and wood weirs); riparian plantings	High
Blenkinsop (5)	Invasive species control, esp. alongside Lochside Trail	Low

Swan Creek not as prone to extremely "flashy" flows, compared to Blenkinsop Creek, due to the attenuating effect of Swan Lake, as shown in Chapter 5, representing opportunities for more feasible channel restoration. For example, Reaches 7 and 8 of Swan Creek, between the Patricia Bay highway and McKenzie Ave. (including the Capital City Allotment Gardens) currently consist of a straight, dug-out ditch that is classified as "non-functional." This area could be transformed to a complex of wetlands and meandering channels, the form it once took (Chapter 2). Creating a wetland in this area would allow greater hydraulic retention time and increased filtration through diverse riparian vegetation and soils (and bioremediation by associated micro-organisms), with the potential to effect a substantial improvement in water quality (Mitsch and Gosselink, 1986). A vision of the creek along these lines was articulated in the late 1960s and early to mid 1970's, when plans for this area entailed restoring a healthy creek with unrestricted public access (van Stolk, 1977; Langford, 1976; Loney, 1973; Loney, 1971; Municipality of Saanich, 1973). As described in a report prepared for the Municipality of Saanich (Townsend, In Press), this site therefore constitutes a potentially rich social-ecological amenity, particularly if this area could one day be connected with Swan Lake Nature Sanctuary with a pedestrian overpass.

Due to limited public land adjacent to much of Blenkinsop Creek, its restoration will be more difficult. Reach 1 represents one of the best opportunities, as it lies within the Swan Lake Christmas Hill Nature Sanctuary, however works in this area will be challenged by erosive flows (see Chapter 5) and will need to be designed accordingly. One possible strategy to improve water quality and dissipate high flows could be to divert a portion of the flow volume through a constructed wetland planted with native species in the Sanctuary, between Leeds Creek and Swan Lake, in areas that are currently dominated by invasive reed canarygrass. Low flows should be the target, since they carry the bulk of contaminants associated with the "first flush" of a rain event, and day-to-day contaminant loading; high flows could bypass the wetland. Reducing nutrient, sediment and toxic inputs to Swan Lake is important to increase the resilience of the clear-water state (i.e. increase the likelihood that a change to this state would occur). Such a project should be funded in part by the municipality, since the area receives flows from a variety of upland sources, including municipal roads. Other reach-scale recommendations are summarised in Table 3.2; watershed-scale recommendations are provided in Chapter 6.

The PFC Assessment Process

Generally, PFC-M is simple to carry out and is considerably less expensive to carry out compared to more detailed hydrological modelling and other engineering or biologically based assessment protocols, although the latter can complement the PFC approach. Furthermore, in PFC-M, "values" or desired uses of the ecosystems, e.g. recreational uses, aesthetics, fish, are not the main focus of the assessment, allowing management decisions that are less prone to stakeholder conflict (Lucey, pers. comm.). As acknowledged by the PFC-M authors, this methodology, like all others, has limitations (Prichard, 1998). Thus far, Aqua-Tex Scientific Consulting Ltd. and their colleagues are some of the first practitioners to apply this method to urban systems; although most principles appear applicable to these systems, there are some key challenges that merit discussion and further investigation.

One challenge of PFC-M is that it is primarily qualitative, and therefore a subjective method, and its effectiveness depends on the ability of the assessment team to adequately judge which conditions are sufficient to impair function and result in a lower rating. In this assessment, I identified two reaches where the initial ratings appeared, upon re-evaluation, to be inconsistent with PFC theory.[6] The main problem (in the first assessment) seemed to be too much emphasis was placed on channel *stability.* Major active erosion was not present, due in large part to a cohesive channel substrate, and to the fact that the streams had been dug out to a size capable of carrying the flows currently experienced. However, upon re-examining the full PFC definition, it was realized that the multiple processes required for 'functional' streams were not present. In this case the error was identified and addressed, but it illustrates the challenge of arriving at consistent results even for an experienced team.

Urban streams in particular present challenges to the assessment methodology, since they are a product of more than just natural interactions between geology, climate, vegetation and flow regime, factors that are themselves highly complex. Direct modification such as channel straightening and lowering, landscaping and vegetation removal can also play a large role (May *et al.*, 1997). Furthermore, urban systems are prone to more frequent high-flow events compared to undeveloped streams (e.g. Baker *et al.*, 2004), therefore the hydrological criteria of the assessment need to be modified, and/or accompanied by additional supporting theory specific to urban streams to allow for proper interpretation.[7]

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6 The team re-assessed these reaches and indeed arrived at a different determination after this process. Reach 1 of Blenkinsop Creek was originally rated as properly functioning and was later re-classified to nonfunctional. Reach 5 of Swan Creek was also originally rated as properly functioning and was later down-graded to functional-at-risk.

7 For example, question #1 in the PFC checklist ("Floodplain above bankfull is inundated in relatively frequent events") is normally answered in the affirmative if the floodplain is inundated on average once every 1.5 years (Prichard, 1998). E.g. in Blenkinsop Creek, high-flow events frequently occur that overtop the channel banks, yet the stream is highly entrenched such that "normal" high-flow events do not access floodplains. Thus other criteria beyond the return period should be applied.

In this assessment (and others by this team) there were lengthy discussions among the group around the concept of stream "potential," which is defined as "the highest ecological status a riparian-wetland area can attain given no political, social, or economical constraints, and is often referred to as the potential natural community (PNC)" (Prichard, 1998). This has proven to be a difficult concept to apply in urban systems, since they are so highly modified that a scenario where humans are not affecting their function is virtually impossible to imagine. The principle of 'potential' seems to hinge on the idea that there is a single trajectory of succession that will play out if a stream is "left alone," whereas multiple trajectories of change appear more likely in light of the dynamic nature of streams.

The Rosgen (1994, 1996) stream channel classification system also has proven difficult to apply in urban environments. Whereas the Rosgen system accounts for abiotic influences on channel form due to topography, sediment transportation and flow regime based on predictive equations, such predictions may not hold in urban systems due to complex hydrological influences (Konrad *et al.*, 2005), and the fact that urban streams are frequently directly modified (e.g. armoured, straightened and excavated). For example, Reach 8 of Swan Creek had the width-to-depth ratio, entrenchment ratio and slope of an "E" channel, however it is a perfectly straight channel (because it has been dug out), whereas natural E channels are highly sinuous. Based on historical evidence (Chapter 2), this reach is thought to have consisted of a wetland that may or may not have included a defined channel. Therefore in the assessment the channel form was simply designated as a "ditch," which is not particularly informative. A classification system could perhaps be developed for urban systems to help with describing their characteristics and understanding stream processes.

Water quality and nutrient processing criteria should also be evaluated when assessing urban areas, to supplement the information from a PFC assessment; research shows that even when riparian plantings and channel restoration are undertaken successfully, critical biological processes can still be impaired in urban streams due to poor water quality (Booth *et al.*, 2004; Walsh *et al.,* 2005). Standard measures can be used to accomplish this, such as chemical water quality analysis, field measurement of physical parameters (e.g. temperature, dissolved oxygen, pH, dissolved/suspended solids, etc.), and indices of biological integrity (Karr and Chu, 1999). Valuable information can also be derived from flow monitoring, as discussed in Chapter 5.

Proper Functioning Condition and Resilience

The definition of PFC stipulates that 'properly functioning' streams are able to dissipate the energy of high flows, through the interactions of channel characteristics (sinuosity, floodplain, rock and wood) and vegetation (root masses capable of stabilising soils and stream banks). Furthermore, stream channels are seen as dynamic systems that *adjust*, with lateral movement and scouring/deposition, and develop characteristics such as floodplains, pools and riffles, that enable them to *absorb* disturbances of high flows without a major shift to a degraded (nonfunctional) state (Prichard, 1998).[8] There is also an implication of thresholds in stream function in the PFC literature, acknowledging the difficulty of restoring the previous state once a particular level of disturbance has been exceeded (Prichard, 1998). Therefore, the definition of PFC could also be articulated in terms of resilience: the amount of disturbance a system can tolerate and still persist, i.e. maintain its functions and controls (Gunderson and Holling, 2002). Thus stream channels may be characterised as having multiple stable states, i.e. PFC and nonfunctional, each of which may have its own resistance and resilience due to self-reinforcing factors (Figure 3.3). Even in an undeveloped watershed, either of the two alternative stable states may be possible (scenario A in Figure 3.3). A major flood, landslide, earthquake or forest fire could shift the stream into a “nonfunctional” state. However, other disturbances over a prolonged period of time (e.g. removal of riparian vegetation, channelization, altered imperviousness and peak flows) may alter the phase-space “landscape” of the probable states (the shaded area in the diagram), making the

8 This is different from a concept of “stability” which implies simply that the channel is not prone to erosion. Stability can be achieved through concrete armouring or enclosure in a pipe, but this does not provide a functional stream that provides the processes and attributes of a healthy and resilient ecological system. This distinction is well articulated in general resilience concepts (e.g. Holling, 1996) but is lacking in urban stream management, where channels are frequently armoured with “hard engineered” structures that prevent lateral channel movement and bank erosion.

basin of attraction around the “functional” PFC state narrower, as in scenario B, in which the PFC state has less resilience. This has the effect of making the basin of attraction defining the degraded state wider or more likely. In this example, scenario B has less resilience (represented by X' in the diagram) due to alteration of watershed characteristics. A “nonfunctional” system may therefore be self-reinforcing due to alterations of the hydrological regime and land use. The “functional-at-risk” state is seen as an unstable condition, where the system may shift either toward “nonfunctional” or PFC.

Accordingly, PFC-M could be used to evaluate ecological resilience of stream channels, however some of the underlying theory should first be updated to reflect current understanding of complex systems and the role of disturbance in maintaining certain

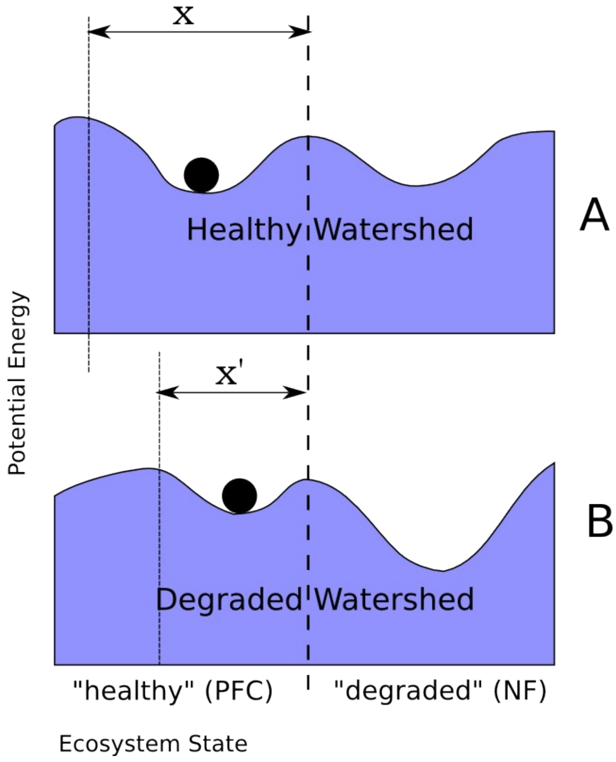

Figure 3.3. Alternative stable states in stream condition, healthy vs. degraded; with X and X' represent the resilience of the healthy state (see text; image by the author)

types of riparian/wetland ecosystems and stream channels (Middleton, 1999; Naiman *et al.*, 1992; Reeves *et al.*, 1996). PFC-M is currently based partly on an assumption that a lotic riparian-wetland system evolves via a single, linear trajectory toward a "potential natural community" that is essentially stable and self-perpetuating, a model that increasingly recognised as overly simplistic (NRC, 1994).

In order to make this connection between the two bodies of research, the PFC-M literature should be updated with additional discussion regarding complexity and systems theory as it relates to the biophysical function of streams. Additional guidance, theoretical discussion and documentation would also be useful to address the problematic concept of "potential" in natural systems (i.e. where multiple stable states may also be conceivable) and to apply PFC-M to urban areas in general. This would help move the theory from a basis in linear succession theory to one that incorporates the dynamic and complex processes and interactions in streams.

3.4. Conclusions

65% of the length of Swan Creek, and 77% of Blenkinsop Creek were rated as either *nonfunctional* or *functional-at-risk*. These portions of the streams do not have appropriate riparian vegetation, channel characteristics and landform to dissipate the energy of high flows and provide the services described in the PFC definition cited previously. Degraded conditions appear mostly related to previous channel modifications (straightening, dredging and culvert installation), loss of riparian vegetation and land use (particularly impervious areas). "Properly functioning" reaches on the other hand were characterised by accessible floodplains, sufficient riparian vegetation to stabilise stream banks as well as appropriate channel form (e.g. sinuosity, width-depth ratio, etc.) resembling the historic or potential condition.

Water quality is not addressed in PFC-M, therefore to be more relevant to urban areas its assessment should be required or at least a highly recommended additional process. A discussion about urban hydrology, and recommended tools to evaluate the altered flow regimes present in urban watersheds, should also be incorporated to PFC-M background and theory literature. The problematic concept of ecosystem "potential" also merits further clarification in the PFC-M literature.

The Municipality of Saanich began a program of land acquisition along Swan Creek and Colquitz Creek in the late 1960s and early 1970s, a program that has saved Swan Creek from being enclosed and has created the potential for restoration. Blenkinsop Creek, on the other hand, has not been subject to this management focus, apparently having been written off as a casualty of urban development long ago. This illustrates the importance of municipal stewardship as well as public awareness.

Despite some success in preserving public land along Swan Creek, large-scale restoration work remains to be carried out, and is necessary to shift the condition of many of the reaches from a degraded ("nonfunctional") state to "proper functioning condition." Despite the challenges of doing so in an urban environment, there are several successful examples within Swan Lake watershed (Malmkvist, 2002; Edmonds, 2002). In effect, this entails a critical intervention to shift the system into a new stability domain where the processes and attributes of a healthy stream are present. Doing so would not only create habitat for fish and wildlife, but also improve water quality discharged into the estuarine and marine environment, and create more valuable human amenities.

Finally, with regard to the study hypothesis, additional work is required to support the theoretical basis of PFC-M in order to explicitly use the system in order to evaluate ecological resilience of the physical structure of stream channels. Complementary methods are also recommended in order to address gaps in PFC-M described above. However, the implicit basis of PFC-M is consistent with resilience theory, potentially justifying efforts to refine an already useful and practical system.

Chapter 4. Vegetation of Swan Lake watershed and wetlands

4.1. Introduction

Plants connect the atmosphere, land and water, thus regulating energy transfer and nutrient and water cycles (Zalewski *et al.*, 2003; US EPA, 2002). A large percentage of precipitation that falls on the land is intercepted by vegetation, evaporated, infiltrated to plant root zones and transpired back to the atmosphere through leaf pores; globally, this “green water” amounts to 65% of the total precipitation that falls on land, yet it is largely ignored by water resource managers (Rockström and Gordon, 2001; Asadian and Weiler, 2007). Plants perform a number of critical ecological functions at both the site and watershed scale that are related to this water flow. Biomass produced through photosynthesis forms the basis of all food chains as well as habitat (including building materials for humans). Root masses and micorrhizae interact with soil organisms, enhance decomposition, bind soils and prevent erosion (Amaranthus, 1999; Atlas and Bartha).

By taking up water from the soil, plants create oxygenated conditions in the soil that further enhance decomposition; the mat of organic material thus created enhances water retention, absorption and infiltration into soils and groundwater (Ripl, 2003). Loss of forest cover at the catchment scale has therefore been recognised to be even more critical than impervious surfaces for explaining degradation of streams and aquatic habitats (Booth *et al.*, 2002). The interrelated processes in a healthy, vegetated watershed, on the other hand, contribute to soil fertility, minimisation of nutrient and sediment loss from surface runoff, and dissipation of solar energy gradients (Bormann and Likens, 1979; Ripl, 2003; Schneider and Kay, 1994), including mitigation of the “urban heat island effect” (Grimmond and Oke, 2005).

Vegetation is examined at two scales in this chapter, the watershed (1200 hectares) and the site at Swan Lake Nature Sanctuary and an adjacent area (51 hectares), due to the importance of nested hierarchies and cross-scale effects to resilience (Holling, 2001).

The research questions for this portion of the study are:

1. What is the current extent of tree canopy and other land cover in Swan Lake watershed, and how has this changed since the earliest records?
2. At the scale of Swan Lake Nature Sanctuary, what are the characteristics of the wetland vegetation community today, according to airphotos, compared to historical airphotos (from 1928 and 1972)?
3. What is the composition of the tall-shrub community at Swan Lake, compared with that of nearby reference sites?

The information from these inquiries is then used to infer possible explanations for differences (and changes) as they relate to site and watershed scale processes, in order to address the second thesis research question.[1] Implications for alternative stable states and resilience are discussed in more detail in Chapter 6.

4.2. Methods

4.2.1. GIS and mapping

Watershed Scale

Mapping at the watershed scale was based on watershed boundaries as delineated by the Municipality of Saanich GIS department. Caslys Consulting Ltd. was contracted to map vegetation and land cover based on data they had already collected for a regional urban forest project (Urban Forest Stewardship Initiative (UFSI), 2008)[2]. The Saanich watershed boundary layer was supplied to Caslys Consulting, whereupon they employed an image analysis software application in an "unsupervised classification" procedure run

1 "How do components of Swan Lake watershed function today, according to vegetation and water-related studies? How do these studies help to evaluate ecological health and/or resilience?" See Chapter 1.

2 This task was contracted out, 1) because the consultant had already compiled data regarding the study area, and 2) because I lacked access to the resources (and the technical background) required to carry out this analysis myself. Funding for this work was provided from the Sara Spencer Research Foundation.

in PCI Geomatica, to identify land cover types from orthophotos, supplied by the Capital Regional District (CRD) and supplemented with land use information (UFSI, 2008; A. Blyth, pers. comm.). The land cover classification was developed in raster format at a resolution of $1m^2$, with a unique cover class assigned to each cell. Where a cell contained more than one cover class, the majority value was used.[3] A summary of the land cover classes used in this analysis is shown in Table 4.1.

The Victoria Official Map for 1858 (discussed in Chapter 2) was georeferenced as closely as possible to present day landscape features, by the Saanich GIS Department. I then delineated polygons representing the various vegetation types noted in the map, using ArcGIS 9.3 at the CRD, with the support of their GIS Department. The land cover classes in this exercise included: open water; riparian/wetland; conifer (Douglas-fir) forest; and deciduous (Garry oak) forest, as summarised in Table 4.2. Some interpretation was required, as the original map did not include a legend describing the symbology used. This map did not cover the entire watershed, since the northern portion fell within what was once the "Lakes District." Therefore, the land cover types north of the map boundary are estimated for the remainder of the watershed, primarily by extending the known (existing) community along a similar topographical gradient.

The land cover from 1858 and from a combination of sources representing the present day were compared. The information sources for the latter are listed beneath the tabulated data (Table 4.4), and consisted of the watershed land classification (based on 2005 orthophotos), and GIS mapping I undertook at the CRD (using ArcGIS 9.3) as well as with the CRD Natural Areas Atlas (public on-line version), based on 2007 orthophotos. There were some discrepancies in the data sources, for example the watershed map produced by Caslys Consulting used provincial TRIM data for the open water value, whereas for the comparison I used the areas I delineated for Swan Lake and Blenkinsop Lake myself. In order to correct for unresolved differences in these two data sources, I reduced the "unclassified" portion for 2005/2007 by a small amount, so that the total

3 The municipal road footprint for the study area was used as the 'uppermost' layer (thus cancelling out overhanging tree cover). This may result in some under-estimation of tree cover, but provides a better estimation of impervious cover, an important attribute in the study (A. Blyth, pers. comm.).

areas in each analysis were equivalent. For 2005/2007, I assumed that conifer forest and Garry oak woodland was limited to the "natural" treed areas remaining in two parks, Mt. Douglas and Christmas Hill. The remainder of the tree cover for 2005/2007 was designated as "urban/residential trees," in order to differentiate this human-dominated "forest" from the native tree cover.

Nature Sanctuary Scale

At the scale of Swan Lake Nature Sanctuary, I classified vegetation types based on a 2007 orthophoto, also using the CRD ArcGIS 9.3 system and orthophotos, with technical support provided by the CRD GIS Department. I included in the analysis the area of land bordering the outflow stream on the west (downstream) side of the Patricia Bay Highway even though it is not within the land managed by the Nature Sanctuary, since this area is important to the past and present function of the lake/wetland system. Designated vegetation and land cover classes included open water, conifer tree, deciduous tree, tall shrub, low shrub, wetland grass, terrestrial grass, aquatic vegetation, cultivated land, "other" wetland vegetation, and miscellaneous non-native species, as described in Table 4.3. Ground-truthing was carried out with field observations and reconnaissance in the summer of 2007. Airphotos were obtained from the National Airphoto Library (for 1928), the Provincial airphoto warehouse (for 1972) and from the CRD (orthophoto for 2007). Airphotos from 1928 and 1972 were georeferenced by the CRD GIS Department, and I classified these with the same vegetation types as for the 2007 orthophoto.[4]

4 The classification was carried out at a scale of about 1:500 for the 2007 airphoto; for the historic airphotos (due to poorer quality), a scale of about 1:1500 was used.

Table 4.1. Land cover classes assigned by Caslys Consulting to watershed airphoto attributes (UFSI, 2007)

Value	Class	Description
1	agriculture	Grass, crop and shrub land covers falling within agriculture and rural residential land uses. The agriculture class includes areas of exposed soil falling within the ALR as these are assumed to be fallow fields.
2	exposed soil	Areas of exposed soil and bare land (e.g., bedrock outcroppings) falling outside agricultural land uses.
3	grass	Grass land cover falling within residential and urban land uses including: lawns, gardens, playing fields and institutional grounds. These areas represent lands subject to regular maintenance.
4	gravel	Areas of exposed soil identified in the TRIM dataset as being an 'extraction' land use. These were all assumed to be gravel pits within the study area.
5	impervious	Impervious land covers are associated with urban areas, residential land uses and other areas of human disturbance (e.g., apartment buildings, industry, single family houses, roads, sidewalks, driveway and parking lots).
6	marsh	Vegetated land covers falling within the areas identified as wetlands in the TRIM dataset.
7	shadow	Areas in the land cover classification unresolved due to shadows in the source imagery that were unable to be classified.
8	shrub	Shrub land cover falling within the residential and urban land uses.
9	trees	Treed land covers.
10	water	Water features identified in the TRIM dataset and other smaller water features (e.g., ponds) identified from the image.

Table 4.2. Land cover classes/interpretations used for 1858 map

Original map notation	Cover class	Description of inferred vegetation
	conifer tree	Douglas-fir dominated forest (mosaic of open and closed forest structure; varying understory)
	deciduous tree	Garry oak dominated woodland; varying from savanna to open forest, grass/forb and/or shrub understory
	riparian/ wetland	Facultative and obligate riparian/wetland species; herbaceous, shrubs and/or trees
	open water	
	cleared land	Grass and/or exposed soil

Table 4.3. Description of vegetation classes used in Swan L. airphoto comparison

Vegetation class	Description
open water	Visible open water (no overhanging canopy)
aquatic veg.	Emergent species fringing lakeshore, e.g. *Typha, Nuphar*
wetland grass	*Phalaris arundinacea* (primarily) *and Glyceria* sp.
low shrub	In wetland areas, primarily *Spiraea douglasii,* var. *douglasii*; in upland areas, various incl. *Symphoricarpos albus; Rubus discolor,* etc.
tall shrub	Primarily *Salix* spp., *Cornus stolonifera, Lonicera involucrata, etc.*
deciduous tree	Various, including *Quercus garryana, Populus balsamifera* ssp. *trichocarpa; Alnus rubra; Populus tremuloides*
conifer tree	Primarily *Pseudotsuga menziesii; Abies grandis*
terrestrial grass	Various species outside of wet (low-lying) areas
cultivated	Under active cultivation
other wetland veg.	Unknown (e.g. in 1928 airphoto); various herbaceous species outside of lakeshore fringe, e.g. *Potentilla anserina; Eleocharis* sp.; *Polygonum* sp.
misc. non-native	*Crataegus monogyna*; various ornamental species; also includes nature house and house within Sanctuary on Swan Rd. (as these were not major landscape elements)

4.2.2. Vegetation Field Survey

Due to budget and time limitations, I was not able to undertake an intensive replicated plot design involving a large number of randomly selected plots around Swan Lake and the comparison sites. Instead, I chose to, 1) carry out a line transect (at Swan Lake only) to examine the gradation in vegetation communities and establish a rationale for the plot-based study, and 2) survey large plots (divided into sub-plots) at discrete locations, that did not require as much time to locate and set up but still allowed some spatial analysis.

Description of Reference Wetlands

Two sites were chosen for comparison with Swan Lake wetlands: Maltby Lake and Prior Lake. These wetlands included a lake of comparable size to Swan Lake, were dominated by tall shrub vegetation, the dominant pre-disturbance vegetation type at Swan Lake, as shown in the pollen study (Townsend and Hebda, In Prep.; Appendix A) and were located within relatively undisturbed watersheds.

Prior Lake is located in the Capital Regional District's Thetis Lake Park, about 7 km west of Swan Lake, in the municipality of View Royal. This lake drains east and south into

Craigflower Creek. No existing reports or assessments of this lake/wetland could be located, and none were known of in the CRD Parks Department. Maltby Lake is located on private property about 2.5 km NNE of Prior Lake, in the municipality of Saanich. It drains north into the Prospect Lake/Tod Creek watershed. Access to the area was granted by one of the landowners on the east side of the lake. This lake/wetland has been fairly well studied and existing reports were reviewed for background (e.g. ENKON, 2002). The physical characteristics of the lakes and their catchments are described in Chapter 5. A reconnaissance survey was made at each site prior to the vegetation study, to ascertain access and general ecological characteristics.

Vegetation Study Methods

The locations of the line transects were chosen subjectively, to coincide with the transects already laid out for the paleoecology study, extending perpendicular to the lake on the northeast and southwest sides (Figure 4.1), as these locations represented some of the largest expanses of wetlands adjacent to the lake. The zero point on the line was located at the first emergent aquatic vegetation encountered adjacent to the open water of the lake, and extended landward as far as the beginning of upland vegetation.

For plot sampling, I modelled the study on a vegetation survey method called the North Carolina Vegetation Survey (NCVS; Peet *et al.*, 1998). Briefly, the NCVS consists of laying out a grid of 10mx10m plots, arrayed in a 2x5 matrix along either side of a baseline. In each plot, species are identified and percent cover is estimated. Woody stems of all shrubs and trees are counted and their diameter at breast height (DBH) is measured. This allows calculation of metrics such as basal area and similar indices of woody plant structure. A “nested” approach of sub-samples is also possible with this method, but I did not employ this part of the technique due to time limitations. The method has been found to be easily scaleable and therefore applicable to a wide range of vegetation types, from grasslands to forest, while the 1000 m^2 total size of the sample area is sufficiently large to be used as an aggregate sample for treed ecosystems (Peet *et al.,* 1998).

Since the tall-shrub vegetation community was the dominant wetland community at the site before the land was cleared, this was the focus of the study. However, a general wetland species inventory was also compiled based on observations of other communities (Appendix C). Two 1000 m^2 grids at Swan Lake were used, in order to cover more than 5% of the shrub community, a minimum recommended percentage (Smith and Smith, 2001).

Woody stem counts are not reported here, since very dense vegetation at the two reference sites prevented a full woody stem count of those plots, and a meaningful comparison with Swan Lake values were not possible due to differing plot sizes. At Prior Lake and Maltby Lake, only four 10mx10m plots were surveyed at each site, due to time and budget constraints; these were laid out in a 2x2 arrangement. In each 10m x 10m plot, a species inventory was completed and percent cover was estimated for each quarter of the plot, in order to more accurately estimate cover in the dense vegetation. Also, this allowed characterisation of the species distribution at a finer (quarter-plot) scale.

Species were identified with the aid of field references (Pojar and McKinnon, 1994; Brayshaw, 1996). All vegetation (except bryophytes) was identified to the species level in most cases, except for a few instances (e.g. *Carex* spp., Brassicaeceae). Species that could not be identified in the field were photographed or physically sampled and shown to experts or compared with herbarium samples and/or on-line resources. A discrete number was estimated for cover, rather than cover classes, in order to avoid problems of inappropriate statistical operations performed with ordinal data in the Braun-Blanquet method (*e.g.* Podani, 2006). The drawback with this strategy is that greater precision than is actually possible to discern may be implied (Wikum and Shanholtzer, 1978), therefore the cover values should be interpreted accordingly. Species covering a very small area, such as a single (small) herbaceous plant in a plot, were assigned a cover value of 0.01%.

At Swan Lake, the locations of the two shrub plot arrays were chosen randomly.[5] I then 'stretched' the grid along the shoreline, since the shrub fringe is too narrow for a double array, and used a 1x10 plot array.

At Prior Lake, I used a similar procedure to choose plot locations, however the possible sample area was limited to a narrower range due to rock outcrops on two sides of the lake. At Maltby Lake, I subjectively chose the location of the plots, since there is only one large wetland. For best comparison with the two other sites, the plot array was oriented as close to the shoreline as possible (while remaining within the shrub community), and the plots were located in the middle of the wetland (from side to side).[6]

Since the sub-plots at each site were not chosen randomly, these do not constitute replicates, rather sub-samples. Also, due to logistical issues, the number of plots sampled at the reference sites, compared to Swan Lake, was not the same. These issues limit the options for statistical analysis to simple metrics, however the information is still useful for a general description to address the research question. Importance value was calculated for all species inventoried, as the sum of the relative cover and relative frequency but did not include density (c.f. McClain *et al.*, 2007; Wikum and Shanholtzer, 1978). This allowed comparison of herbaceous and woody species.

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5 From the centre of the lake (taken to be the deepest point as shown on bathymetric maps), I chose a compass heading using an online random numbers program (www.random.org). Certain areas were ruled out due to the topography (rocky outcrops) or a width less than 10m, the width of a single cell. The bearing taken from the centre determined the starting point, and the baseline was laid out in a 'clockwise' direction from that point, in a straight line.

6 Randomly choosing the plot location would have introduced more error, for example by increasing the likelihood of including upland influences by locating it too close to either side.

Figure 4.1. Location of vegetation study plots and line transect at Swan Lake, in relation to other field sites

4.3. Results

4.3.1. Watershed Scale Vegetation and Land Cover

The land cover classification from the 2005 orthophoto is shown in Figure 4.2. The largest cover class is tree cover (26%), followed by impervious surfaces (25%), grass (19%) and agriculture (16%). (Note that the "shadow" category (10%) represents uncertainty in the other categories.) These results confirm that the landscape is dominated by human use. Although the land use was not classified into more detailed development categories, it is apparent from the airphoto that residential development, agriculture and transportation (roads) are the main land uses, with several commercial centres represented with a high proportion of impervious surfaces.

The pre-development land cover is shown in Figure 4.3. The dominant vegetation type at that time was the Garry oak (*Quercus garryana*) community, which covered 51% of the watershed. Conifer dominated forest covered 33% of the watershed, followed by wetland/riparian areas at 13%; rock formed 1.5%, and only one small area of cleared land was present (3.4 hectares or 0.3% of the area). In order to compare this with the present-day attributes, I combined information from the watershed map produced by Caslys Consulting with GIS mapping I undertook[7] (Table 4.4). The most obvious difference is the loss of 88% of the conifer forest, and nearly 100% of the Garry oak savanna/woodland. Note that many trees remain as part of the developed landscape, estimated to cover another 19% of the watershed, however ecological processes and functions of this treed area have been significantly changed and thus it should be considered separately. Another significant change is the reduction in wetland area, from 154 hectares in 1858 (13% of the watershed), to 49 hectares today (4% of the watershed). "Cleared areas," which are considered to be a combination of exposed soil, agriculture and grass-covered land, now constitute 35% of the watershed. As previously stated, impervious surfaces also form a major element in the present-day landscape. These changes are also shown as pie charts in Figure 4.4.

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7 Thus the present day is represented by "2005/2007"; the different information sources also resulted in some discrepancy such as a slightly different open water value, as stated in the Methods section.

4.3.2. Swan Lake Wetlands - Airphotos

The airphoto analysis is shown for 1928 (Figure 4.5), 1972 (Figure 4.6) and 2007 (Figure 4.7), and differences in the categories are summarised in Table 5.5.[8]

In 1928, a large area of the wetlands was already under cultivation, and the inflow and outflow streams had both been partially channelized. A notable feature of this image is the apparently undisturbed vegetation in the SW corner of the Sanctuary. This was assumed to be a combination of the following, based on their appearance and known vegetation types in the area, pollen analysis (Townsend and Hebda, In Prep.) and species present at the site (currently and in the past):

- Deciduous trees at the southernmost edge, likely dominated by red alder (*Alnus rubra*) and black cottonwood (*Populus balsamifera* ssp. *trichocarpa*), possibly intermixed with western redcedar (*Thuja plicata*) and shrubs from the adjacent community.

- Tall shrubs (and small trees) north and west of the deciduous trees, likely including willow (*Salix* spp.), red osier dogwood (*Cornus stolonifera*), Pacific crabapple (*Pyrus fusca*), birch (*Betula* sp.), black twinberry (*Lonicera involucrata*), etc. Low shrubs could also be intermixed in this community, e.g. *Spiraea* sp., *Rosa nutkana*, *Physocarpus capitatus*, etc.

- Bordering the tall shrubs is an unknown herbaceous wetland community classified as “other wetland vegetation.” This vegetation does not have a “clumpy” structure as would be expected with shrubs, therefore it seems likely to be a rush/sedge (*Cyperaceae*) community, possibly with sweet gale (*Myrica gale*) and other low-growing species such as buckbean (*Menyanthes trifoliata*) and Pacific water parsley (*Oenanthe sarmentosa*). This community could be similar to the herbaceous lakeshore communities observed at Prior and Maltby Lakes as

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8 Although the perimeter of the study area was kept constant for most of the area, there were small changes primarily due to the expansion of the road footprint of the Patricia Bay highway (west of Swan Lake), therefore the total area shows a decrease over the period. Also, a minor error was made in the 2007 mapping, leaving out a small area.

described below, and may be classified as Wf53, a “slender sedge - white beak-rush” fen according to McKenzie and Moran (2004).

- Along the lakeshore is a floating aquatic community, probably consisting of some of the above-listed species as well as pond lily (*Nuphar* and/or *Nymphea* spp.), cattail (*Typha latifolia*) and hard-stem bulrush (*Schoenoplectus lacustris*), among others.

- As described in Townsend and Hebda (In Prep.) and Appendix A, wetland grass was not likely a significant component of the pre-disturbance vegetation community, however by 1928 introduced species could have invaded or been cultivated in some areas.

By 1972, very little native vegetation remained, and the cultivated area had increased from 19 to 23 hectares, plus an additional 6 hectares designated as “wetland grass,” at least some of which is probably reed canarygrass, which was well established by the early 1970s (Zaccarelli, 1975). There were large losses of tall shrubs and deciduous trees in particular. By this time, the outflow stream had been straightened and dug out completely. In 1975, the Swan Lake Christmas Hill Nature Sanctuary was formed, therefore this airphoto is a good representation of the condition of the area soon before conservation practices were implemented.

The 2007 airphoto (Figure 4.7) shows substantial changes from 1972. Cultivation is limited to the area adjacent to the outflow stream (Swan Creek), within the Capital City Allotment Gardens. Otherwise, shrubs and deciduous trees have replaced some previously cultivated areas. However, the wetland grass component (largely reed canarygrass) increased from 6.2 to 13.7 hectares, in areas that were previously cultivated. The “misc. non-native” category has also increased, due to a dense growth of English hawthorn (*Crataegus monogyna*) on the west side of the lake, and a residential property at the end of Swan Rd.[9] The total wetland area was estimated by summing the wetland-

9 Note that the latter polygon includes the house itself, as structures were not considered an important attribute of the study.

related vegetation communities (aquatic vegetation, wetland grass, low shrub, tall shrub, deciduous tree, conifer tree, other wetland vegetation and cultivated)[10,11] giving a total of 37 hectares. As shown in Table 4.6, today the reed canarygrass community comprises 14 hectares or 38% of the wetland area, and the tall shrub community (once likely the dominant vegetation) covers 26% of this area.

In the early 1980s, restoration was carried out along Swan Creek adjacent to the lake, and along "Darwin Creek," an inflow stream that joins Swan Creek from near the municipal Hall; this entailed planting and re-construction of channel meanders (T. Morrison, pers. comm.). Some planting and channel restoration was also later carried out along Leeds Creek, a small inflow stream in an area east of Saanich Rd. (Edmonds, 2002). Otherwise, the changes in vegetation shown in these airphotos occurred for the most part without human intervention. The vegetation in 1972 and 2007 is compared more closely in Figure 4.8. Some expansion of the tall shrub community surrounding the lake is evident, and the homogeneous character of the cultivated fields has become more complex with colonisation with various types of vegetation. Low shrubs (mostly hardhack) have colonised a fairly large area in the NW corner of the area, along with smaller areas of tall shrubs in this area. Thus it appears that some "recovery" of native vegetation has occurred in this area, however it is to a large degree different from the pre-disturbance vegetation community, a remnant of which is apparent in the 1928 airphoto, and as described in Chapter 2. The main difference apparent at the scale of the airphotos is the loss of large areas of tall shrubs and trees, and persistence of the wetland grass community.

4.3.3. Swan Lake Wetlands and Reference Sites - Ground Level Study

Line Transects

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10 Strictly speaking, come of the conifers, deciduous trees and low shrubs may be terrestrial species in small areas, however overall (at Swan Lake) the wetland portion of these communities dominates; thus there is some error in this estimate but it is thought to be small.

11 To enable a comparison of the composition of the wetland vegetation in the three years represented in the airphotos, the values for 'cultivated' areas for 1972 and 1928 were reduced slightly (a justifiable procedure since terrestrial areas were also cultivated).

The line transect data for the South site is summarised in Appendix C. Reed canarygrass was by far the most dominant species in this area (relative dominance (RD) was 78, followed by red osier dogwood at a RD of 5). The strong gradation in vegetation is also apparent in this data, varying from a thin fringe of aquatic species (yellow pond lily and cattail), through a wider band of tall shrubs composed of Pacific willow (S. *lucida* ssp. *lasiandra*), red osier dogwood, Sitka willow (S. *sitchensis*) and Scouler's willow (S. *scouleriana*), followed by a very wide expanse of reed canarygrass monotype, to the beginning of the upland zone, marked by Himalayan blackberry (*Rubus discolor*). Reed canarygrass also had the widest range at this site (227 m), defined as the distance between its first and last occurrence along the transect.

In the north transect, more species were present, since the transect crossed through a willow "island" outside of the lakeshore fringe, which also contains other species. Reed canarygrass was still the most dominant (RD=50), with Pacific willow the next most dominant (RD=9.9), followed by spikerush (*Eleocharis* sp.) (RD=5.2) and red osier dogwood (RD=5.1), with other species ranking below these. The presence of Pacific silverweed (*Potentilla anserina*) and spikerush was notable as these species are not particularly common in other areas at Swan Lake. There are also several "weedy" species such as mustard (Brassicaeeae), beggarticks (*Bidens* sp.), yellow parentucellia (*Parentucellia viscosa*), cudweed (*Gnaphalium* sp.), dandelion (Asteraceae) and thistle (*Cirsium* sp.), probably a legacy of past disturbance through cultivation (Hebda, Pers. Comm.).

These transect results show that, at least in the areas sampled, where reed canarygrass occurs it is nearly 100% exclusive of other species. The composition of the tall shrub community was characterised in general terms, and was found to consist largely of several willow species and red osier dogwood, with little herbaceous understory. Reed canarygrass, giant mannagrass (*Glyceria maxima*) and European bittersweet (*Solanum dulcamara*) were prevalent within the aquatic community as well as intermixed in more open areas of the shrub stands. These findings enabled a more focused study of the shrub community, since the reed canarygrass could for the most part be assumed to be monotypic (not requiring more detailed inventory); the aquatic community was also of interest, to compare with less disturbed areas, but time constraints only permitted a qualitative study.

Shrub Plots

In general, the Swan Lake North (SL-N) site had a large proportion of Pacific willow trees, some of which were quite large (ca. 65 cm diameter at breast height). Sitka willow and red osier dogwood were also common. The understory was sparse and generally consisted of annual species such as willow herb, with the exception of openings that had thick reed canarygrass and/or mannagrass. The Swan Lake South (SL-S) site had more dense, and smaller-diameter woody vegetation that consisted of more red osier dogwood and Sitka willow, as well as Geyer's willow (*S. geyeriana*) and Hooker's willow (*S. hookeriana*). There was less grass in the understory, compared to SL-N, and little other herbaceous cover.[12]

The wetlands at Maltby Lake and Prior Lake were similar to one another, in having very dense woody vegetation growth that was dominated by willow (*S. sitchensis* and *S. geyeriana*) and red osier dogwood as well as hardhack. There was much more herbaceous cover than at Swan Lake, especially skunk cabbage (*Lysichiton americanus*) and slough sedge (*Carex obnupta*).

These observations are quantitatively expressed as a summary of cover at each site (Table 4.7). The cover values (for all species with cover greater than 5%) are also compared over all four sites in the graphs shown in Figure 4.9. Neither reed canarygrass nor mannagrass were noted at Prior or Maltby Lake, whereas they ranked among the species with highest cover at Swan Lake. As previously noted, skunk cabbage and slough sedge rank high in the total (mean) cover values at Maltby and Prior Lakes, and were not present at Swan Lake.[13]

The importance values for each species are shown in Appendix C. At both Maltby Lake and Prior Lake, hardhack ranked highest, followed by skunk cabbage. At Maltby Lake,

12 Additional observations included several trees recently chewed by beavers and a family of river otters.

third most important was red osier dogwood, followed by Sitka willow and slough sedge. At Prior Lake, Sitka willow was third, followed by Geyer's willow and red osier dogwood. At Swan Lake, Pacific willow had the highest importance value at SN-N, and red osier dogwood at SL-S, however invasive species rank highly at both sites. Giant mannagrass, reed canarygrass and European bittersweet (all invasive species) rank second to fourth in importance value at SL-N, while European bittersweet ranks third at SL-S, followed by reed canarygrass.

As shown in Table 4.8, in general woody species cover was lower at both Swan Lake sites (70% and 93%) compared to Prior and Maltby Lakes (103% and 113%), however these differences were not tested for significance (since the overall plot sizes were different and sub-plots were not randomly sampled). The reference sites also did not have any invasive species, and had very little grass, whereas reed canarygrass, giant mannagrass and European bittersweet were very common at the Swan Lake sites, as mentioned above. Herbaceous species other than grass had high cover values at both Maltby Lake and Prior Lake, and zero at both Swan Lake sites.

Historical Inventories: Swan Lake and Blenkinsop Lake

Two reports were consulted that inventoried wetland vegetation at Swan Lake in the early to mid 1970s (Shepherd, 1975; Zaccerelli, 1975), as listed in Appendix C. These species are compared to observations I made in the course of general field work. Several species that were present in the past and that were *not* observed in this study include: water plantain (*Alisma plantago-aquatica*); wapato (*Sagittaria cuneata*); skunk cabbage (*Lysichiton americanus*); marsh cinquefoil (*Comarum palustre*); buckbean (*Menyanthes trifoliata*); speedwell (*Veronica* spp.); and earth loosetrife (*Lysimachia terrestris).* There were other "missing" species, but they are more inconspicuous and could have been more

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13 Note that the sampled areas are different between the Swan Lake site (1000m2 total area) and Maltby and Prior Lakes (400m^2). This could result in patches of vegetation at the smaller sites skewing the results toward higher values than might be found at a larger spatial scale; for example, this could be the case for hardhack, which does have quite a patchy growth form (however, it did appear to be common throughout the general area at each site). There could also be a greater chance of missing more rare species at the smaller sites, although more species (at >5%) were still noted at Maltby and Prior Lakes than at either Swan Lake site.

easily overlooked, whereas this is less likely for most of the other species.

Some species not listed in these historical inventories and observed in 2007-2008 include: western redcedar (*Thuja plicata*); red alder, black cottonwood; trembling aspen (*Populus tremuloides*); Kellogg's sedge (*Carex keloggii*); silverweed; salmonberry (*Rubus spectabilis*); slough sedge (*Carex obnupta*); baldhip rose (*Rosa gymnocarpa*); clustered rose (*R. pisocarpa*); English holly (*Ilex aquifolium*); English ivy (*Hedera helix*); English hawthorn (*Crataegus monogyna*); field bindweed (*Convolvulus arvensis*); giant mannagrass (*Glyceria maxima*).[14] Some of these species were only recently planted, as noted in the table, while the latter five listed are invasive species. Existing willow species that were identified, in addition to the Pacific willow and generic "*Salix* spp." listed in the 1975 reports, included Scouler's willow, Sitka willow, Geyer's willow and Hooker's willow.

The historical Blenkinsop wetland vegetation is listed in Appendix C for general comparison purposes, as a detailed analysis of this data is beyond the scope of this study. There are commonalities with past and/or present species at Swan Lake, including willow, birch, hawthorn, aspen, cottonwood, hardhack, red osier dogwood, cattail, skunk cabbage, bulrush, pond lily, marsh cinquefoil, Pacific water parsley, and silverweed. Species noted at Blenkinsop Lake that were absent at Swan Lake include Sitka spruce (*Picea sitchensis*), shore pine (*Pinus contorta* var. *contorta*), western hemlock (*Tsuga heterophylla*), red elderberry (*Sambucus racemosa*); lady fern (*Athyrium filix-femina*); and several rush (*Juncus* spp.) and sedge (*Carex* spp.) species. Also, Blenkinsop Lake hosted a number of bog species, including round-leaved sundew (*Drosera rotundifolia*), swamp laurel (*Kalmia sp.*), Labrador tea (*Ledum groenlandicum*), wintergreen (*Gaultheria procumbens*)[15] and dwarf blueberry (*Vaccinium caespitosum)*. Labrador tea and round-leaved sundew were observed during this study at Maltby Lake, in addition to

14 Mannagrass currently present at Swan Lake was positively identifed as *G. maxima* (a non-native species) by Dr. Richard Hebda at the Royal B.C. Museum, based on comparison with herbarium specimens. *G. grandis* (a native species) is listed in the 1975 inventory, and may have been mis-identified.

15 There is some doubt as to the identification of this species as it is normally an eastern species; more likely it is *Pyrola asarifolia* (N. Turner, pers. comm.).

bog rosemary (*Andromeda polifolia*), as listed in Appendix C.

Species that were common to both Blenkinsop Lake and Swan Lake historically (i.e. in the 1970s) include Sitka willow, Geyer's willow, Hooker's willow, Scouler's willow, red alder, Pacific crabapple, red osier dogwood, hardhack, Pacific water parsley, skunk cabbage, rush (*Juncus* spp.), cattail, buckbean, and marsh cinquefoil.

Table 4.4. Watershed vegetation and land cover, 1858 compared to 2005/2007

	1858		**2005/2007**	
	Area (ha)	%	Area (ha)	%
open water (Swan L. & Blen L.)	17.4	1.46	15.8	1.33
conifer forest	391	32.9	46.6	3.92
Garry oak woodland	605	50.9	4.93	0.42
Rock	17.5	1.47	17.5	1.47
wetland (Swan L. & Blen. L.)	154	13.0	49.0	4.13
cleared land	3.40	0.29	417	35.1
Urban/residential trees & shrub			226	19.0
Impervious surfaces			291	24.5
unclassified (shadow)			120	10.1
Total	1188	100	1188	100

See footnote for methods of calculating 2005/2007 landcover[16]

16 Conifer forest and Garry oak woodland are remnant "native" communities, in Mt. Douglas Park and Christmas Hill, delineated with CRD Natural Areas Atlas (NAA). Rock areas delineated with CRD NAA, subtracted from overlaid vegetation polygon in 1858 data. Swan L. wetland area (37 ha) delineated by L.T. (see below); Blenkinsop wetland delineated with CRD NAA (12 ha). Cleared land calculated as sum of Caslys data for agriculture, exposed soil and grass, minus grass area of wetlands. 'Urban/residential trees & shrubs': Caslys tree cover minus tree cover in wetlands and conifer/GO areas. Impervious surfaces are from Caslys data. Unclassified was adjusted (reduced) by 4 ha to equal total A for 1858 (to compensate for error in above calcs.).

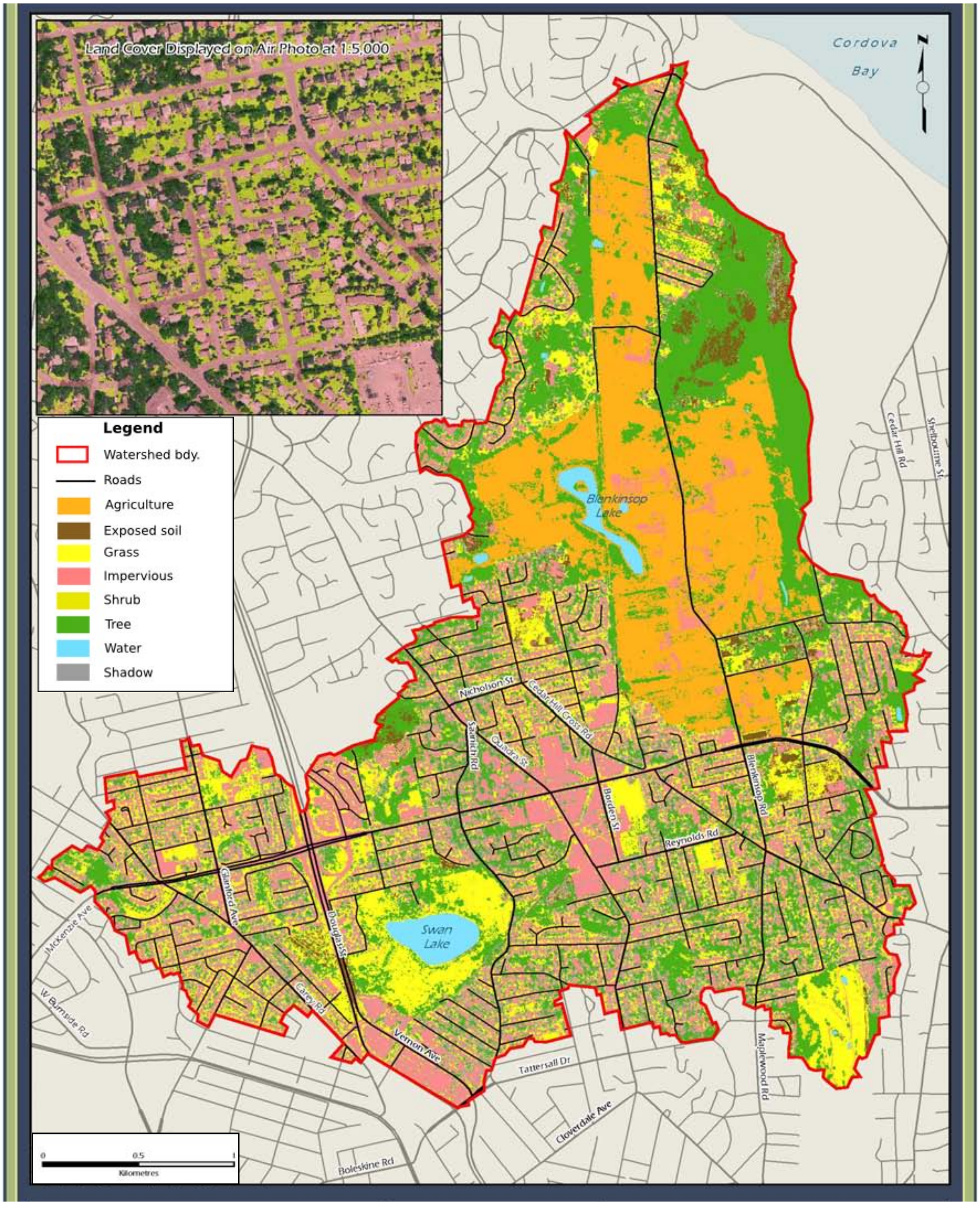


Figure 4.2. Swan Lake watershed land cover, 2005 (Caslys Consulting Ltd.*)
** NB: completed on contract for L. Townsend; used with permission*

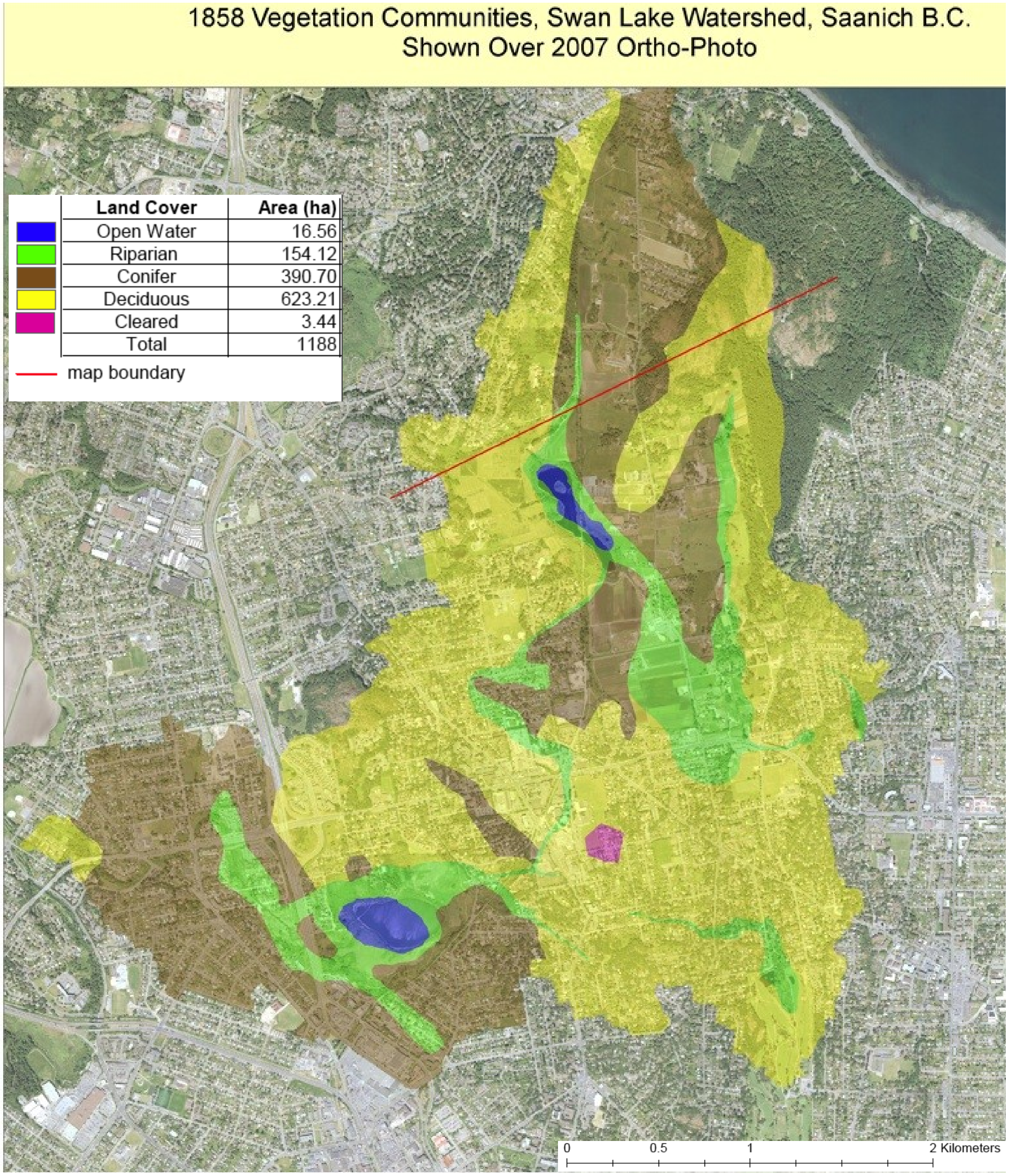
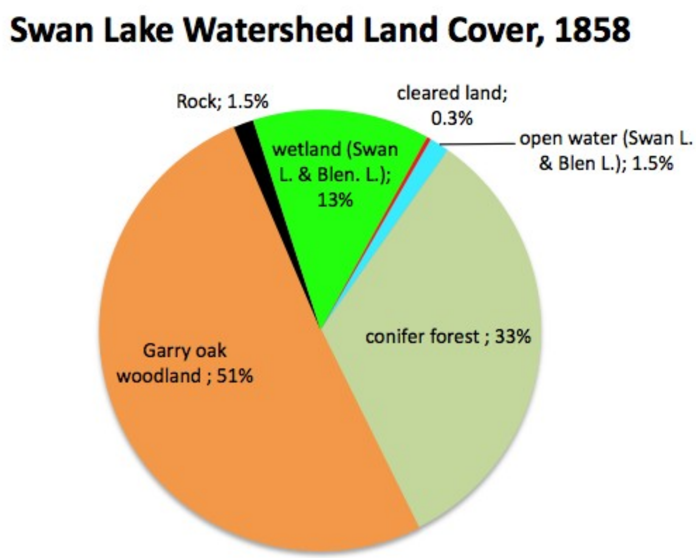


Figure 4.3. Swan Lake watershed, vegetation communities from 1858 Victoria Official Map (by L. Townsend)



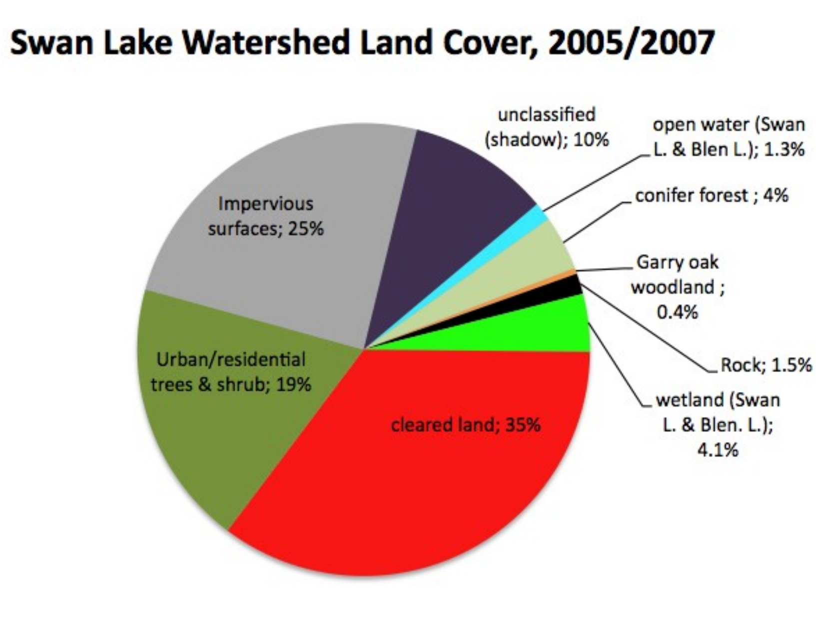
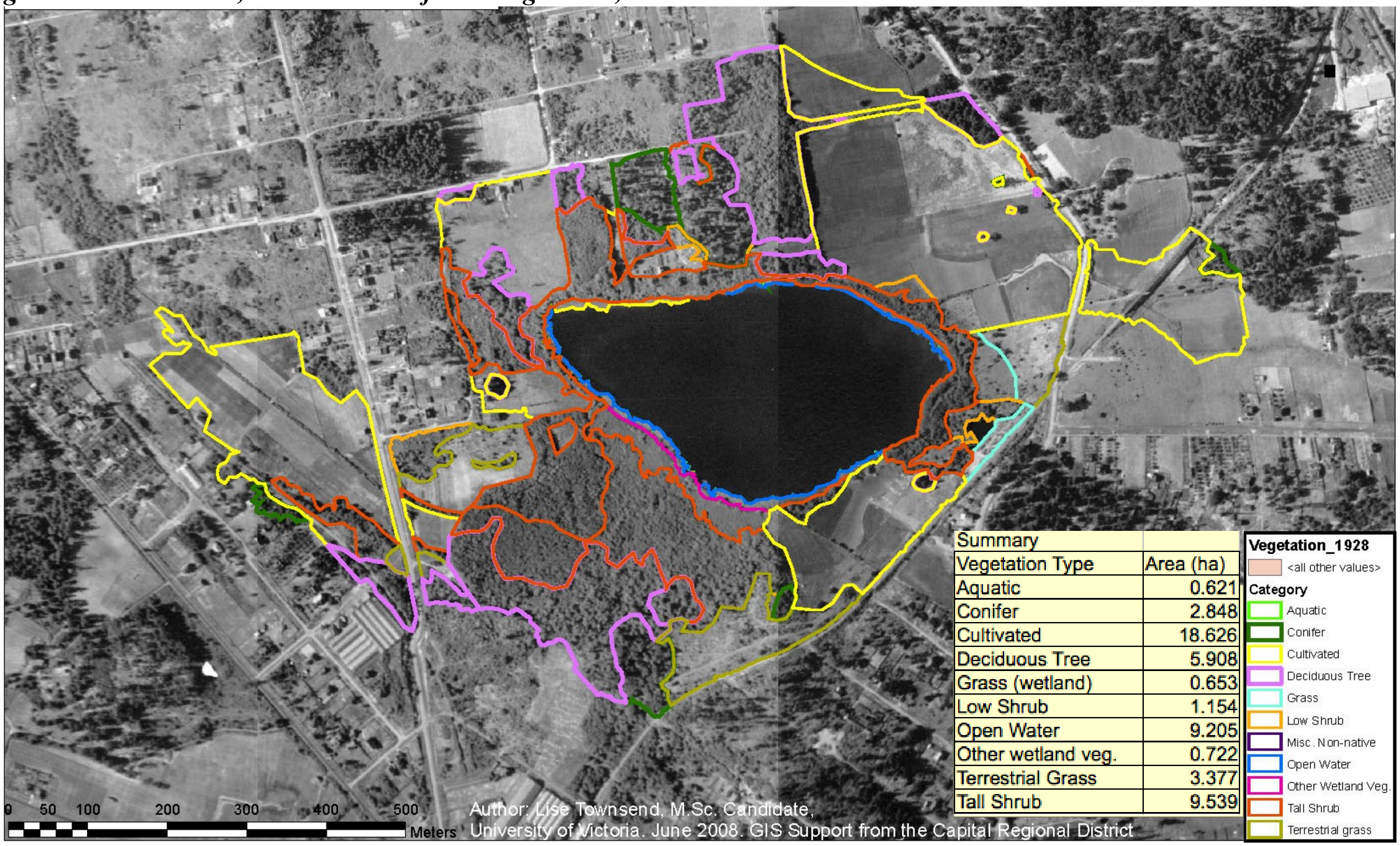
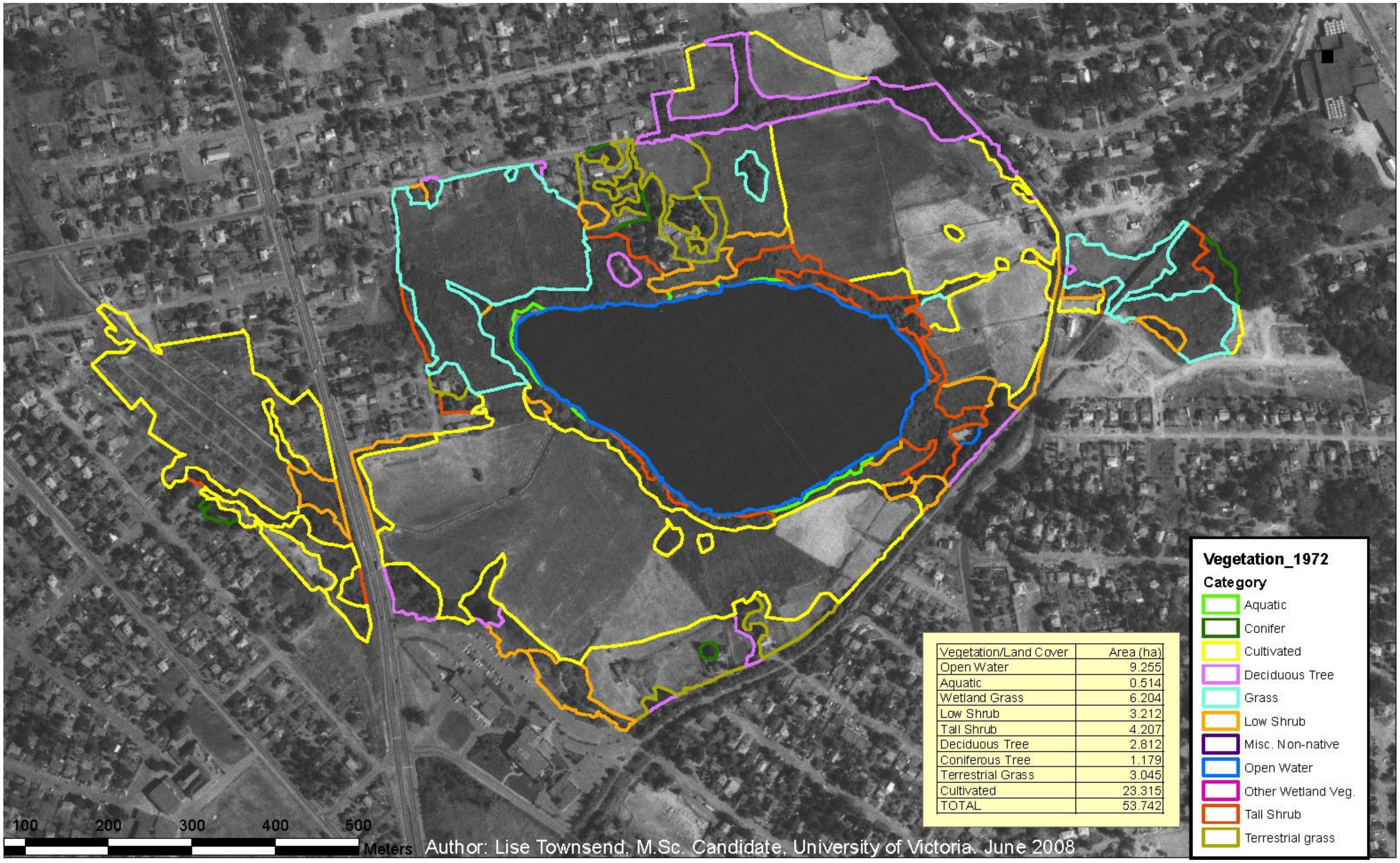


Figure 4.4. Swan Lake watershed land cover, 1858 (top) compared to 2005/2007 (bottom)

Figure 4.5. Swan Lake, wetland and adjacent vegetation, 1928

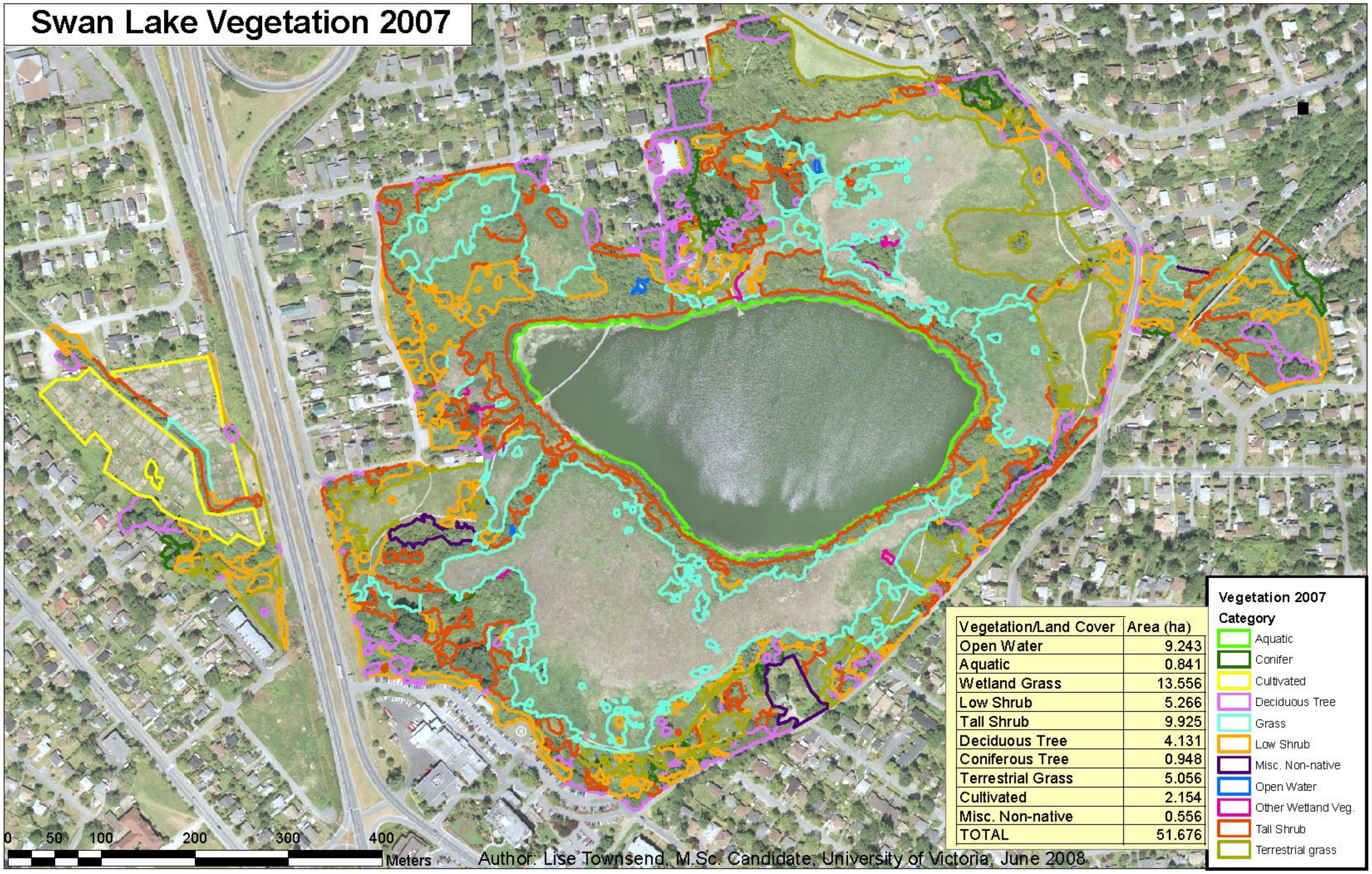


Summary	
Vegetation Type	Area (ha)
Aquatic	0.621
Conifer	2.848
Cultivated	18.626
Deciduous Tree	5.908
Grass (wetland)	0.653
Low Shrub	1.154
Open Water	9.205
Other wetland veg.	0.722
Terrestrial Grass	3.377
Tall Shrub	9.539



Vegetation/Land Cover	Area (ha)
Open Water	9.255
Aquatic	0.514
Wetland Grass	6.204
Low Shrub	3.212
Tall Shrub	4.207
Deciduous Tree	2.812
Coniferous Tree	1.179
Terrestrial Grass	3.045
Cultivated	23.315
TOTAL	53.742

Figure 4.6. Swan Lake, wetland and adjacent vegetation, 1972



Vegetation/Land Cover	Area (ha)
Open Water	9.243
Aquatic	0.841
Wetland Grass	13.556
Low Shrub	5.266
Tall Shrub	9.925
Deciduous Tree	4.131
Coniferous Tree	0.948
Terrestrial Grass	5.056
Cultivated	2.154
Misc. Non-native	0.556
TOTAL	51.676

Figure 4.7. Swan Lake, wetland and adjacent vegetation, 2007

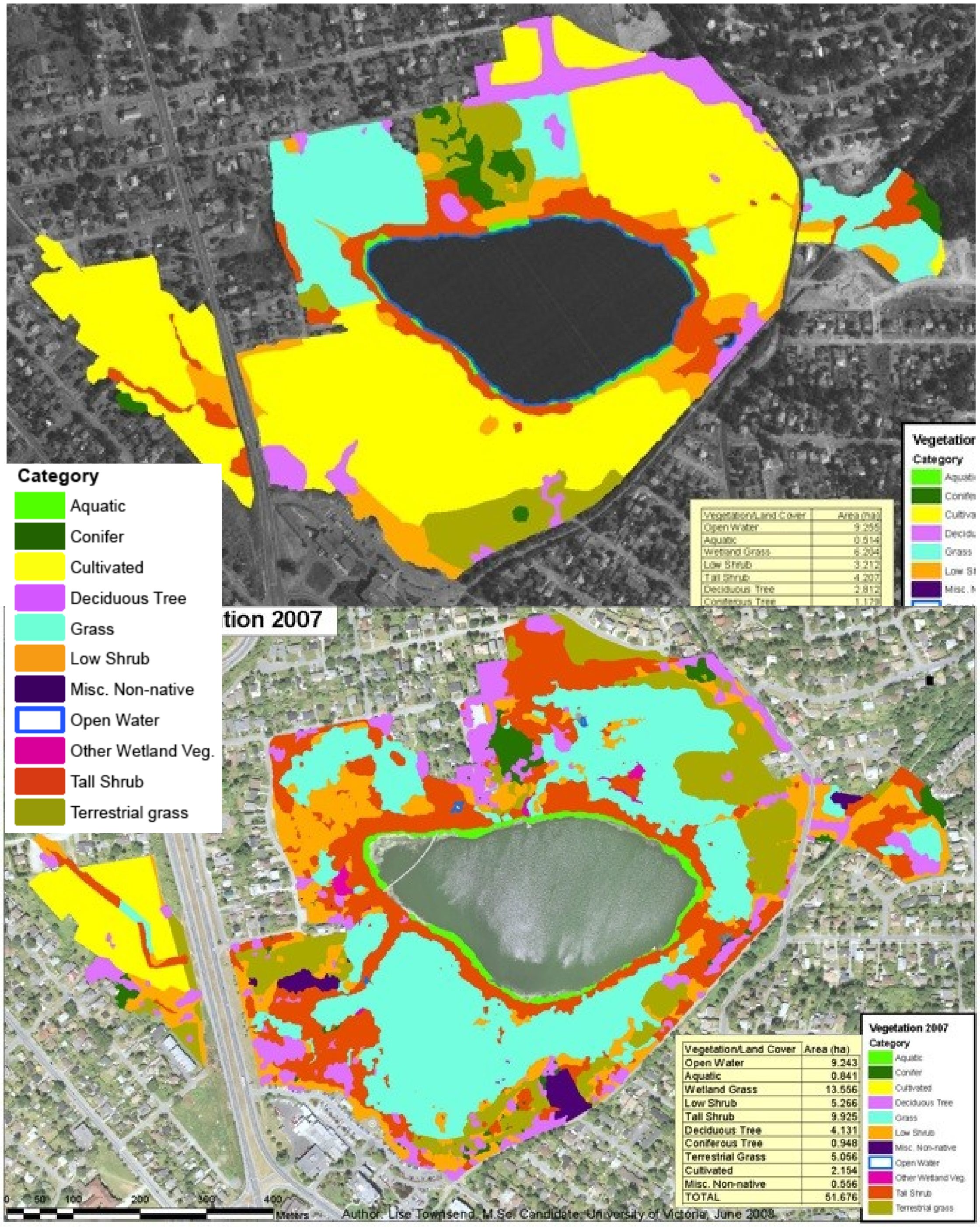


Figure 4.8. Comparison of Swan Lake vegetation in 1972* (top) and 2007 (bottom)

*note: scale on 1972 map is not exactly matched with 2007 scale

Table 4.5. Comparison of vegetation & land cover classes in Swan Lake wetlands, 1928, 1972 and 2007 (in hectares)

	1928	1972	2007
open water	9.21	9.26	9.24
aquatic veg.	0.621	0.514	0.84
wetland grass	0.653	6.20	13.67
low shrub	1.15	3.21	5.25
tall shrub	9.54	4.21	9.92
deciduous tree	7.27	2.81	4.13
conifer tree	2.53	1.18	0.95
terrestrial grass	3.38	3.05	5.06
cultivated	19.35	23.3	2.15
other wetland veg.	0.722	0	0.24
misc. non-native	0	0	0.56
Total	*54*	*54*	*51*

Table 4.6. Comparison of wetland vegetation composition in 1928, 1972 and 2007

	1928		1972		2007	
Vegetation Type	**area (ha)**	**%**	**area (ha)**	**%**	**area (ha)**	**%**
aquatic veg.	0.621	1.67	0.514	1.38	0.84	2.26
wetland grass	0.653	1.76	6.20	16.71	13.7	36.79
low shrub	1.15	3.11	3.21	8.65	5.25	14.13
tall shrub	9.54	25.67	4.21	11.33	9.92	26.7
deciduous tree	7.27	19.57	2.81	7.57	4.13	11.12
conifer tree	2.53	6.8	1.18	3.17	0.95	2.55
cultivated*	14.67	39.48	19.0	51.19	2.15	5.8
other wetland veg.	0.722	1.94	0	0	0.24	0.65
Total	37	100	37	100	37	100

**cultivated area reduced in 1972 and 1928 for this calculation to enable total wetland area to equal 2007; justified as terrestrial areas were cultivated*

Table 4.7. Wetland species list and cover in plots at Swan Lake, Prior Lake and Maltby Lake

			Cover (%) by Site			
	Code	Species	SL-N[1]	SL-S[1]	Maltby[2]	Prior[2]
Woody spp.	Slu	*Salix lucida* ssp. *lasiandra*	49	8.1		
	Ssi	*Salix sitchensis*	11	20	20	20
	Ssc	*Salix scouleriana*	1.1	3.3		0.94
	Sge	*Salix geyeriana*		4.2	13	21
	Sho	*Salix hookeriana*		0.7	1.1	6
	Sba	*Salix babylonica*		0.15		
	Cst	*Cornus stolonifera*	5.0	51	23	7.8
	Sdu	*Solanum dulcamara*	2.0	3.0		
	Sdo	*Spiraea douglasii* var. *douglasii*	2.1	2.5	53	42
	Sal	*Symphoricarpos albus*	0.0003			
	Lin	*Lonicera involucrata*			3.8	1
	Rur	*Rubus ursinus*			0.25	
	Aru	*Alnus rubra*			1.1	2.1
	Pfu	*Pyrus fusca*				1.1
	Rnu	*Rosa nutkana*				0.56
	Rdi	*Rubus discolor*	0.025			
Herbaceous spp.	Par	*Phalaris arundinacea*	26	8.2		
	Gl	*Glyceria* sp.	25	0.0008		
	Lam	*Lysichiton americanus*			23	26
	Ag	*Agrostis* sp.		4.8	0.44	
	Cob	*Carex obnupta*			17	1.0
	Ju	*Juncus* sp.			3.6	
	Ca	*Carex* sp.[3]			1.8	0.57
	Afi	*Athryium filix-femina*			1.6	0.47
	Ep	*Epilobium* sp.	0.075	0.078	0.0006	
	Br	Brassicaceae	0.012			
	As	Asteraceae	0.00025			
	Osa	*Oenanthe sarmentosa*	0.00025	0.027		0.033
	Po	*Polyganum* sp.	0.00025			
	Tla	*Typha latifolia*		0.15		
	Ga	*Galium* sp.		0.0008		
	Sp	*Sparganium* sp.		0.0003		
	Bi	*Bidens* sp.		0.013		
	Sla	*Schoenoplectus lacustris*		0.0050		
	Cfr	*Crystopteris fragilis*			0.06	0.0006
	Vpa	*Viola palustris*			0.0013	0.004
	Paq	*Pteridium aquilinum*			0.063	
	Mar	*Mentha arvensis*				0.32

1. Study plot size 1000m2; sub-plot size 25m2, n=40
2. Study plot size 400m2; sub-sample size 25m2, n=16

Figure 4.9. Comparison of main wetland vegetation species cover at Swan Lake (N and S sites), Prior Lake and Maltby Lake

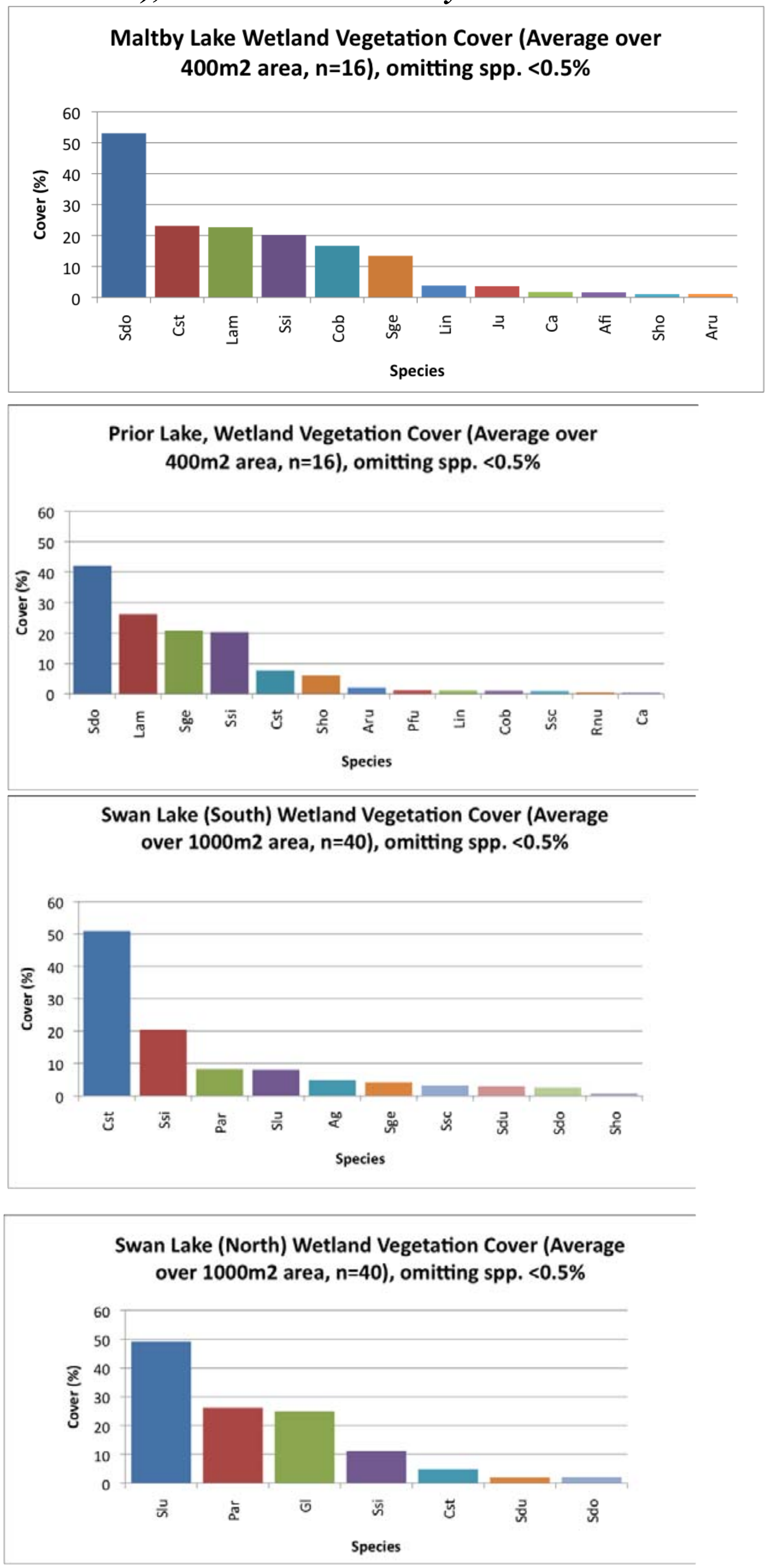


Table 4.8. Comparison of % cover of vegetation types in study plots at Swan L., Maltby L. and Prior L.

	SL-N	SL-S	Maltby	Prior
woody species	٧٠	٩٣	١١٣	١٠٣
tall shrub/tree[1]	٦٦	٨٧	٤٣	٥٦
low shrub[2]	٢	٣	٥٣	٤٢
woody vine[3]	٢	٣	٠	٠
grass species	٥١	١٣	tr	٠
perennial herbaceous (excl. grass)	٠	٠	٤٧	٢٨
invasive species[4]	٥٣	١٦	٠	٠

1. *Salix spp.; Cornus stolonifera; Pyrus fusca; Alnus rubra*
2. *Spiraea douglasii,* var. *douglasii*
3. *Solanum dulcamara*
4. *Solanum dulcamara; Phalaris arundinacea; Glyceria maxima*

4.4. Discussion

According to the 1858 map and other sources (see Chapter 2), the watershed prior to and soon after European settlement consisted largely of a combination of Garry oak communities (savanna, woodland and/or open forest) and conifer-dominated forest, with two large wetlands and several smaller wetlands and riparian corridors. Therefore woody vegetation probably covered 80 to over 90% of the study area.[17] Riparian/wetland areas (also dominated by woody vegetation[18]) were formerly a significant landscape element, and covered 16% of the watershed; this proportion has been reduced to 4% today (Figure 4.4). In the past, the forested and wetland areas would have therefore effected substantial evapotranspiration, and limited surface runoff and nutrient loss, although there would have been subtle differences between the different terrestrial communities in this regard, and variability across a heterogeneous landscape. The wetlands would have helped to trap sediment and nutrients and provide nodes of high productivity and diversity in the watershed. Several wetlands were converted to agriculture and urban land use, including

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17 The actual number would depend largely on the structure of the Garry oak community, i.e. savanna vs. woodland.

18 Although parts of some wetlands consisted of herbaceous species, overall, shrubs and trees dominated riparian/wetland areas.

the large wetland south of Blenkinsop Lake, and two smaller wetlands.[19] In these areas, much of the water, sediment and nutrients are now conveyed directly to downstream areas with ditches and stormwater pipes. The wetlands around Swan Lake have been protected as a park, however as discussed below the characteristics of those wetlands have been largely altered.

The watershed vegetation mapping indicates that as of 2005/2007, tree cover was around 26%; however, of this cover, less than 2% consisted of “natural” Garry oak communities, and around 16% consisted of conifer-dominated forest.[20] The remaining tree cover was classified as “urban/residential” tree cover (Table 4.4). The latter still performs important functions, including carbon sequestration, air pollution removal, and rainwater interception and infiltration (McPherson *et al.*, 1997), and in this case it is composed in part of native species. However, the urban forest cover merits separate discussion, since the management of these trees will determine to a large degree their function in the landscape. Residential areas typically contain of a large percentage of ornamental species, which are often less valuable for wildlife habitat and other ecological services, and require increased maintenance such as fertilisation and watering (Turner *et al.*, 2005). In many cases, trees planted along boulevards and in dense commercial areas are cut off from soil nutrient and water supplies, which can limit growth and impair tree health (Watershed Forestry Resource Guide, 2008).

“Cleared land” (mostly mown grass and agriculture) today covers 33% of the land area and the total impervious area is around 25%. Since terrestrial grass and agricultural crops have much less biomass and leaf area compared to woody vegetation, they generally do not as effectively sequester carbon, mitigate air pollution or contribute to cooling via evapotranspiration, particularly in urban areas where soil disturbance and harvesting of crops occurs (Pokorný, 2001; McPherson *et al.*, 2008).

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19 One was located where the Saanich Public Works Yard currently lies, the other in the east part of the wetland, draining from today's Cedar Hill golf course.

20 For the purposes of this discussion, “natural” means these areas consist of a sizeable contiguous ecosystem with a primarily native understory, not part of residential properties and street-scapes.

Total imperviousness is frequently correlated with aquatic ecosystem degradation, however the actual relationship between this attribute and ecological health depends on many factors such as the permeability of the native soils, and the design of the urban drainage network (Walsh *et al.*, 2005; McBride and Booth, 2005). Imperviousness affects not only the runoff characteristics of the watershed but also the energy balance (i.e. contribution to heat island effect) and ecological functions due to replacement of a multi-functional living landscape with hard surfaces that serve only limited social/economic objectives.

The cumulative changes in vegetation cover in the watershed indirectly indicate substantial reduction of the "green water" portion of the water cycle, and consequently reduced rainwater interception, evapotranspiration and localised evaporation-condensation cycles, and increased surface runoff (the latter as discussed in Chapter 5). In Vancouver, urban trees, in particular native conifer species, have been found to intercept up to 30% of annual rainfall, reducing surface runoff and costs associated with stormwater conveyance and flood control, and contributing to improved water quality (Asadian and Weiler, in press). As described above and in the following chapters, solar and hydraulic energy is dissipated by healthy vegetated ecosystems. Vegetation clearing leads to increased temperature and energy gradients, contributing to urban heat island effect, as well as regional (and ultimately, global) changes in weather and climate processes (Scheffer *et al.,* 2005). This in turn results in increased air conditioning needs, a technology that is itself energy and water-intensive, and has health consequences due to reduced air quality and heat-related illness and deaths (McPherson *et al.,* 1994). Although these may not seem like large concerns in a temperate climate, heat waves in such areas could be particularly serious since many buildings do not have air conditioning and the populace is not accustomed to or prepared for a heat emergency. Furthermore, the problem is likely to worsen with climate change (Bates *et al.*, 2008) and expanding development in the watershed with population growth in upcoming decades. Some possible strategies for restoring "green water" flows in Swan Lake watershed may include incorporating more perennial vegetation in landscaping and agriculture, restoring riparian and wetland areas where possible, and implementing “water sensitive urban design” and green infrastructure for managing water as an integrated resource, as described in more detail in Chapter 6.

As shown in the pollen study (Townsend and Hebda, In Prep.; Appendix A), woody vegetation (particularly willow and associated tall shrubs) was the dominant vegetation in the lakeshore wetlands at Swan Lake prior to agricultural disturbance. A remnant of this vegetation is evident in the 1928 airphoto (Figure 4.5), along with a herbaceous community that is no longer present. Much of this and other vegetation was cleared for agriculture, as shown in the 1972 airphoto where 68% of the wetland area has been cleared and is either actively cultivated or covered in 'wetland grass', likely reed canarygrass (Table 4.6). Since 1975 when the nature sanctuary was formed, some native vegetation communities have re-colonised certain areas in previously cultivated fields, and some riparian areas have been replanted successfully with trees and shrubs. However, large expanses of reed canarygrass have persisted over about 14 hectares (38% of the wetlands) for the past 33 years. Reed canarygrass was probably originally planted as a fodder crop (Zaccarelli, 1975), and was not likely present in the pre-agricultural vegetation community (Townsend and Hebda, In Prep.). Although it may or many not be (strictly speaking) an exotic species, it is highly invasive, particularly where water levels fluctuate widely and where nutrient and sediment inputs are high (Kercher and Zedler, 2004). These conditions are also unfavourable for sedge (*Carex* spp.) (Kercher and Zedler, 2004), which may have been part of the unidentified herbaceous wetland community visible in the 1928 airphoto. Thus restoration of the complete historical vegetation community may not be possible, yet as shown in the pilot project summarised in Appendix D, woody vegetation is a good candidate for replanting.

The Capital City allotment gardens along Swan Creek represents the only floodplain area that is still cultivated around Swan Lake today, and in this area the stream channel still takes the form of a straightened ditch with little adjacent riparian vegetation. The loss of native woody and herbaceous vegetation represents a loss of complexity in habitat structure and species composition.

The composition of the shrub community at Swan Lake was compared with reference sites at Prior Lake and Maltby Lake. The plots at Swan Lake had a high proportion of invasive species, primarily reed canarygrass, giant mannagrass and European bittersweet. The reference sites had no invasive species and had an understory of perennial herbaceous species (mainly skunk cabbage and sedge), that were lacking at Swan Lake. Other studies have shown a loss in wetland species diversity and an increase in invasive monotypes with increased anthropogenic stress (Frieswyk, 2005; Kercher and Zedler, 2004). Diversity among those species that are key for maintaining the physical structure of a system confer resilience to disturbance (Holling, 1986). In the reference wetlands and in the shrub plots at Swan Lake, tall woody shrubs (especially red osier dogwood and willow) are primarily responsible for maintaining the physical structure of the vegetation community, while the understory plays a secondary role in recovery from disturbance. For example, at Swan Lake, the presence of reed canarygrass in the understorey may impede resilience of the shrub stand, for example by expanding and preventing re-growth in the event of a major disturbance such as a fire or windstorm. This effect is perhaps analogous to the role of a seedbank, which Frieswyk (2005) found to be important for predicting the future resilience of lakeshore wetlands. In the reference wetlands, in contrast, the native understory species present are less aggressive and would not be expected to impede germination of new woody shrubs.

The invasive grass-dominated state of the wetlands at Swan Lake (outside the shrub community) may therefore represent an alternative stable state that is self-maintaining due to the aggressive growth habits and wide tolerance of reed canarygrass to various soil moisture, nutrient and flooding regimes (Frieswyk, 2005; Kercher and Zedler, 2004). In this case, resilience of the undesired state impedes natural re-establishment of the native vegetation community, and must be overcome for successful restoration.

Historical species inventories at Swan Lake were compared with the 2007 study plots and reconnaissance surveys, suggesting that several species have likely been extirpated from the wetlands, including skunk cabbage, buckbean and marsh cinquefoil. The latter two species in particular are generally associated with low to moderate nutrients (McKenzie and Moran, 2004), and it is not surprising that they would be absent, given the current highly eutrophic conditions at Swan Lake. These species may also be intolerant of the flooding/drawdown regime currently experienced in the lake, influenced by the watershed characteristics (Chapter 5). In general, the species at Swan Lake are indicative of disturbance from the previous agriculture and land clearing, and degraded water quality. The site-level study highlights the importance of examining landscape characteristics at a variety of scales and considering the history of the site, as from an airphoto perspective the nature sanctuary wetlands might be assumed to be "natural" and relatively healthy.

4.5. Conclusions

Vegetation and land cover in Swan Lake watershed has been transformed through processes of urbanisation, such that today 50% of the watershed consists of a combination of impervious surfaces (25%), agriculture and grass-covered areas (33%). Tree cover is approximately 26%, however only a few small areas consist of intact native-dominated 'forest'. Wetland area has been reduced from 16% of the watershed, to 4%, due to drainage and filling for agriculture and urban development.

As discussed in Appendix A, the wetlands at Swan Lake were likely dominated by willow and associated tall shrubs before agricultural disturbance; agriculture is apparent in the 1972 airphoto, at which time 68% of the wetlands had been cleared of native vegetation. Today, some natural and human-assisted recovery of native species has occurred, but invasive grass (primarily reed canarygrass as well as giant mannagrass) still covers 38% of the wetland area.

Species composition of the shrub-dominated vegetation community at Swan Lake (represented by two large study plots) indicates that several woody species dominate (Pacific willow, Sitka willow and red osier dogwood) however invasive species (reed canarygrass, giant mannagrass and European bittersweet) are also widespread. Aside from the invasive grasses, other herbaceous species were sparse in the Swan Lake study plots. Several previously documented wetland species in the area appear to have been extirpated. In two reference sites in undisturbed wetlands at Maltby Lake and Prior Lake, dominant woody species included hardhack, Sitka willow, Geyer's willow and red osier dogwood, however perennial herbaceous species cover was also high at these sites, especially skunk cabbage and sedge species. The invasive grasses at Swan Lake are likely a legacy of agricultural disturbance (directly and/or indirectly), and as indicated by their persistence, may be limiting natural expansion of the shrub ecosystems. This study suggests that at Swan Lake wetlands, even among the native shrub-dominated community, invasive species may be limiting vegetation diversity and impeding resilience of a native species dominated state, while the large expanse of reed canarygrass at Swan Lake represents an alternative stable state, compared to one dominated by native shrubs.

Considered as a whole, the land cover changes likely represent a significant alteration of energy, water and nutrient cycles. At the watershed scale, a loss of woody vegetation and proliferation of impervious surfaces, combined with accelerated conveyance of surface flows with pipes and ditches, represents reduced evapotranspiration and increased likelihood of nutrient- and sediment-laden runoff. At the Swan Lake site scale, cessation of agriculture has likely mitigated erosion and nutrient runoff from these areas, however a change from woody to herbaceous vegetation persists and may represent a reduction in the services performed by the former, such as carbon sequestration, air pollution uptake and cooling with evapotranspiration. While some of these alterations may be necessary to support a dense human population, the social/ecological costs may be substantial, and are rarely considered.

Chapter 5. Present Day Hydrological Patterns and Processes

5.1. Introduction

The effects of land use changes on watershed hydrology are explored in this chapter, through analysis of the lake level and stream flow patterns in Swan Lake and its main inflow/outflow streams, investigation of water quality, and comparison of some of these attributes with less disturbed systems. Implications for ecological resilience are then discussed in more detail in the following chapter.

As shown in the previous chapter, Swan Lake watershed is approximately 25% impervious. Urban watersheds with a high percentage of impervious area[1] experience high peak flows and low summer flows, and steep peaks in response to rainfall events, due to fast runoff from impervious surfaces and low hydrological storage (Paul and Meyer, 2001). In contrast, forested watersheds have more attenuated peaks/lows and runoff is delayed by interception with vegetation, evapotranspiration, infiltration and storage in soils (Leopold, 1968). The former scenario results in a suite of problems and due to cumulative effects and feedbacks, this has recently been referred to as the "urban stream syndrome" (Walsh *et al*., 2005). These effects are well described and include:

- increased surface runoff and peak flow events (Burges *et al.*, 1998);
- increased mobilisation and transportaiton of nutrients such as nitrogen and phosphorus (Wollheim *et al.*, 2005);
- erosion, enlargement and aggradation of stream channels (Hammer, 1973; Leopold *et al.*, 2005);
- conveyance of urban pollutants into aquatic ecosystems and toxicity effects on aquatic biota (Paul and Meyer, 2001);
- degraded aquatic biological conditions and reduced biodiversity, for example loss of sensitive species such as salmonids (Morley and Karr, 2001; May *et al.*, 1997).

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1 Imperviousness may be measured in either "total impervious area" or "effective impervious area" - the latter is a measure of the impervious areas that are directly conveyed to receiving waters, and although more important for watershed hydrology can be difficult to measure accurately (Center for Watershed Protection, 2003).

Direct impacts are also important and exacerbate many of the problems described above. For example, removal of large wood, channel straightening and enclosing portions of channels in culverts, and removing riparian vegetation, all serve to further accelerate flows and contribute to erosion and degradation of water quality (Leopold *et al.*, 2005).

Although these general trends are well known, to date there has been little hydrological information collected for the Swan Lake watershed, therefore the extent to which the urban character influences ecological processes is unknown. Furthermore, notwithstanding improved knowledge of urbanisation effects, integrated solutions and perspectives derived from an understanding of ecological and hydrological processes at the catchment scale are rare (May *et al.*, 1997; Krauze and Wagner, 2007). As described in Chapter 1, few studies have thus far explicitly linked watershed processes to resilience theory.

Hydrology is closely tied with water quality, as stated above, since surface runoff transports urban pollutants, nutrients and sediment into streams and lakes. Swan Lake is a highly eutrophic lake, and water quality has been studied extensively over the years, however few studies have thus far considered processes relevant to water quality occurring at the landscape or watershed scale. Therefore this study focused on physical water quality parameters (dissolved oxygen, temperature, pH, conductivity, total dissolved solids, secchi depth), which give a general picture of lake processes, and compared these with results from two nearby reference sites, lakes of similar size that are located in forested watersheds. Budget and time constraints did not permit detailed chemical analysis of water quality, however recent water and sediment chemistry sampled by other researchers is summarised.

The primary hypothesis tested in this chapter was: **Hydrological study of the stream flow and lake levels in response to rainfall (graphically represented in a hydrograph), combined with water quality analysis, will show evidence of the effects of urbanisation, that is useful for restoration and management.**

The second hypothesis tested was: **Results from the hydrological/water quality study**

can be used to develop surrogate measures of resilience.

The objectives of this portion of the study were to:

1. Plot the hydrographs of the inflow/outflow streams and of Swan Lake, and relate these to watershed processes and characteristics;

2. Compare the changes in lake levels in Swan Lake with those in a relatively undisturbed reference lake (Maltby Lake), and infer causes for differences.

3. Measure water quality (in terms of physical parameters) and compare these with two references lakes (Maltby Lake and Prior Lake); and summarise general findings from other studies of water chemistry.

4. Synthesize these findings to elucidate possible alternative stable states in watershed-related systems and investigate potential metrics for ecological resilience (this objective is addressed in Chapter 6).

Overview of Watershed, Lakes and Streams

Swan Lake consists of a 9.2 hectare lake, with a maximum depth of about 5m. It is surrounded with grass- and shrub-dominated wetlands covering about 37 hectares (Chapter 4), as well as smaller areas of upland vegetation, within a 48-hectare nature sanctuary.[2] Watershed characteristics were summarised in previous chapters. Blenkinsop Lake, 6.2 hectares in size, is located to the north of Swan Lake, and is connected to it via Blenkinsop Creek. A weir located downstream from Blenkinsop Lake is operated by the municipality to maintain lake volume storage over the summer, and is removed over winter. Few alternative stormwater systems are in place and therefore most of the surface runoff from impervious areas is conveyed directly into the streams and lake via storm drains. Although Blenkinsop Creek is the main inflow stream to Swan Lake, several other smaller storm drains empty into wetlands adjacent to Swan Lake (see Figure 4.1). The unique outflow stream draining Swan Lake is called Swan Creek. Between the

2 This area includes only the portion of the Sanctuary surrounding Swan Lake; additional area is encompassed in the Christmas Hill portion of the Sanctuary. Note, the vegetation study in Chapter 4 included an additional area outside of the sanctuary.

Patricia Bay Highway and the Swan Creek gauging station, a large parcel of municipally owned land alongside both sides of the stream is cultivated as allotment gardens. Swan Creek joins Colquitz Creek about 1.5 km upstream from its discharge point in Portage Inlet, a marine estuary. Limited numbers of coho salmon (*Oncorhynchus kisutch*), chum salmon (*Oncorhynchus keta*) and cutthroat trout (*Oncorhynchus clarki clarki)* spawn in Colquitz Creek and in the lower reaches of Swan Creek (Victoria FGPA, pers. comm.; BC MoE FISS, no date).

5.2. Methods

General Description and Rationale

The discharge of a stream over a period of time is used to characterize the flows it conveys, and is normally represented in a hydrograph. I used the area velocity method (Rantz *et al.*, 1982) to calculate the discharge (in m^3/s) of the streams over the study period (August 2007 to July 2008) by measuring the cross-sectional area of the channel and multiplying it by the velocity of the water (area in m^2 x velocity in m/s = discharge in m^3/s). Stream stage was continuously monitored with an electronic sensor and datalogger, as was lake level.[3] A series of velocity and depth measurements were made at various times throughout the year, using a Marsh-McBirney Flo-Mate velocity meter loaned by the Capital Regional District, and a stage-discharge rating curve was developed. This enables calculating the discharge from any river stage using the formula of the plotted curve .

Rainfall was monitored at the Victoria School-Based Weather Station network (Weaver and Wiebe, 2007), at several nearby stations, as shown in Table 5.1.

3 The sensor were Odyssey™ capacitance probes, and were set to take half-hourly readings; sensors were mounted inside a PVC pipe and metal housing. A V-notch weir was also installed in Swan Creek to measure low flows (see Appendix E for details).

Table 5.1. Summary of school-based weather station locations

Station	Swan Lake (Lancaster St.)	Lake Hill Elementary	Reynolds High School
Latitude (N)	48 27'49”	48 28'43”	48 28'11”
Longitude (W)	123 22'41”	123 21'56”	123 21'35”
Approx. direction & dist. from Swan L	W 0.2km	NNE 1.7 km	NE 1.1 km

Lake level is a measure of cumulative inputs of surface water, groundwater and precipitation. Changes over a year, factored over the surface area of the lake, represent change in storage (volume) in the lake, and the hydrological pattern of flood and drawdown has effects on wetland vegetation (e.g. Van der Valk and Davis, 1973).

Physical parameters of water quality are useful as they are inexpensive to monitor, and reflect biochemical attributes of lake ecosystems. Parameters measured in Swan Lake and two reference lakes (Prior Lake and Maltby Lake) included temperature (°C), dissolved oxygen (mg/L), pH, conductivity (µS/cm), total dissolved solids (mg/L) and oxidation/reduction potential (mV).

Site Descriptions

Hydrological monitoring stations were set up at four locations (Table 5.2). GPS coordinates and elevations were measured at Swan Lake, Blenkinsop Creek and Swan Creek by Saanich Engineering staff, using a Trimble 5800 unit calibrated to a benchmark station at Mt. Douglas, with an accuracy of +/- about 4cm. The Maltby Lake site was GPS located using a Garmin 60CSX handheld unit (accuracy +/- 4m); an exact elevation was not available for this site, but the lake is at about 60m ASL (BC Ministry of Environment, 1982). Station locations at Swan Lake are shown in Figure 4.1.

Table 5.2. Summary of gauge location coordinates, elevations and descriptions

Site	**Swan Lake (II)**	**Blenkinsop Cr.**	**Swan Cr.**	**Maltby Lake**
Latitude (W)	48º 27'51.140"	48º 27'51.743"	48º 27'51.018"	48º29'48.23"
Longitude (N)	123º 22'28.604"	123º 21'56.729"	123º 22'59.239"	123º26'56.92"
Elevation (m) @ 0.0m on gauge	11.01	13.946	11.64	approx. 60
Location Description	~ 50m E. of floating boardwalk, north shore	Upstream of confluence with Leeds Cr., E of Lochside trestle	Downstream of allotment gardens (Kent St. bridge)	NE side of lake @ 4434 Prospect Lake Rd (manual gauge only)
Physical site character-istics	Near lake edge, mounted to scaffold in ~1.5m water, soft organic substrate	Moderately entrenched stream; slope ~2%; high rainfall events cause flooding outside channel	Highly entrenched stream (all flows contained); slope ~1%; V-notch weir installed	Near lake edge, mounted to pier of private dock

Note a few potential sources of error associated with the site locations and logistics of sampling:

- One disadvantage of the Blenkinsop Creek site is that flows over-topping the banks do occur in intense rainfall storms, making measurements above this level inaccurate with the area-velocity method (this likely occurred during the largest rainfall events of the year).
- In Swan Creek, thick growth of vegetation in the channel represents a potential source of error in flow calculations (Rantz *et al*., 1982).
- The Swan Lake site was the second site used, installed after the original site was vandalized; this resulted in the loss of some data, as the initial elevation of the gauge had not yet been georeferenced to a datum.
- At Maltby Lake, the resident of the property, Mr. Thompson, took daily manual readings, which I compared to readings at the same time of day in Swan Lake (This site consisted only of a manual staff gauge.) Due to personal illness on his part, some data is missing during the summer.
- Due to logistics required to measure velocity with borrowed equipment, only four

velocity measurements were taken during the study period, whereas a minimum of 6 is recommended for an accurate hydrological study (Rantz *et al.*, 1982).

Water quality was sampled near the middle of Swan Lake, near the deepest point as noted on bathymetric maps (BC Ministry of Environment, 1981b). All sites were accessed by kayak. Prior and Maltby Lakes were chosen as reference sites based on subjective criteria including: proximity to Swan Lake, for similar weather and climate influences and accessibility; (roughly) similar size of open water; presence of a sizeable adjacent woody wetland, for vegetation comparison (see Chapter 4); and an undeveloped catchment. Prior and Maltby Lakes are both higher in elevation than Swan Lake, making them imperfect comparison sites, however there are no other undisturbed, low-elevation lakes nearby. Physical characteristics of these lakes are summarized below (Table 5.3). It should be noted that all of these lakes are likely influenced to some degree by groundwater, which was beyond the scope of this study.

Table 5.3. Summary of physical characteristics of lakes studied

	Swan Lake	Prior Lake[2]	Maltby Lake[1]
Surface area (m^2)	97925	59200	70500
Maximum depth (m)	6	5	8
Mean depth	2.4	2.6	4.1
Volume (m^3)	237530	155700	291600
Perimeter length (m)	1340	1030	1181
Elevation (m ASL)[3]	12	53.3	60
Catchment Area[4] (ha)	998	229	219
Approx. area of adjacent wetlands[5]	23	1.7	4.6
Parent watershed	Colquitz Creek	Craigflower Creek	Tod Creek

Sources:
1. BC Ministry of Environment, 1982
2. BC Ministry of Environment, 1981a
3. BC Ministry of Environment, 1981b (Maltby and Prior L), Saanich GIS (Swan Lake)
4. For Swan Lake, GIS mapping by Saanich (see Chapter 5); for Prior/Maltby Lakes, estimated from CRD Natural Areas Atlas; includes only the land area draining to Swan Lake, not including Swan Creek downstream of the lake.
5. For Swan Lake, GIS by L. Townsend (see Ch.6), for Prior/Maltby Lakes, est. from CRD Natural Areas Atlas

5.3. Results

The total monthly rainfall measured at Swan Lake was approximately 30% less than the 29-year average recorded at the Environment Canada Gonzales station (Environment Canada, 2002), as shown in Figure 5.1. These values are measured in rain, not precipitation, since the school-based stations rely on tipping gauges that do not directly record snowfall. In total, from August 1, 2007 to July 31, 2008, 417.8 mm of rain were received at Swan Lake, versus an average of 583.1 mm at Gonzales. (Average precipitation at Gonzales is 607.6 mm.) The only month where rain during the study period exceeded the average was December 2007, largely because of a single rain event on December 3-4.[4]

Based on flow measurements and cross-sectional area, the stage-discharge rating curve and line equations for Blenkinsop Creek and Swan Creek are shown in Figure 5.2 and Figure 5.3. The R^2 value for the Blenkinsop Creek curve is 0.998, indicating good agreement between the data and the plotted line (thus the expected accuracy of the equation). At Swan Creek, a less ideal relationship was found (R^2=0.831) possibly due to thick vegetation (reed canarygrass) in the channel that confounded consistent flow measurements. The high flows of December 4, 2007 represent the highest rain values of the study period, with a maximum flow calculated at 11.7 m^3/s in Blenkinsop Creek.[5] Since detailed quantitative analysis of this data is beyond the scope of this study, the main focus of discussion is the general shape and character of the graphs and magnitude of change (e.g. reaction time to rainfall events, and rate of increase/decrease), as shown in Figure 5.2 and Figure 5.3 for the year.

Blenkinsop Creek is clearly a highly reactive system, with very marked peaks in response to rainfall. Although some small rain events appear to have little effect, larger events, particularly over the winter when the ground in the watershed is saturated, result in

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4 This comparison may be subject to error due to differences in the equipment between the two weather stations, and varying levels of quality control.

5 However, this value may not be very accurate, since it was extrapolated beyond the range of the measured flows used to generate the rating curve.

practically instantaneous response in discharge.[6,7]

Swan Creek, in contrast, had only a few obvious peaks in response to the largest rainfall events of the season, and smaller rain events had little apparent effect on flows. However, smaller scale changes in discharge are apparent in the graph representing flow through the V-notch weir (Figure 5.4). Fluctuations are evident in the early part of the summer in this graph, when relatively small rain events occurred regularly, and storage in the lake was still high. Once a long dry period began in late June, a strong decreasing trend in stream flow is evident, through to late August.

During winter rain patterns, the difference between the character of flows in the two streams is more apparent. Figure 5.7 shows both hydrographs plotted together with rainfall for several rain events in December 2007 to January 2008. These are relatively low-magnitude events, with daily rainfall not exceeding 2mm (in contrast, daily rainfall exceeding 15mm is not uncommon in normal winter storms). Blenkinsop Creek flows track the rainfall patterns closely, with extremely steep rising and falling limbs of the hydrograph. Swan Creek, on the other hand, responds more gradually, and there is a greater delay between the onset of rain and the response of the stream flow volume.

The higher resolution data presented in Figure 5.8 also show this behaviour, during a single low-intensity rainfall event in November. Rainfall began on November 11 at 0434, and lasted until 1158 that morning, with a total of 12mm accumulated in the event. Between 0921 and 1058, Blenkinsop Creek experienced a 5000% increase in discharge, with a slope (between the two points) of 0.05. In contrast, discharge in Swan Creek over the same period increased only 119%, with a slope of 0.000104 (calculation not shown).[8] Another way to represent stream discharge response to rainfall is the “lag time,” which is

6 Note that where the graphs suggest that stream response sometimes seems to precede the rainfall event, this is probably a result of rainfall having already occurred higher in the watershed (and not yet recorded at the Swan Lake station).

7 I also noted fast response of the stream empirically when conducting flow measurements during a rain storm, and observed the stream level rise at a rate of approximately 10 cm per minute over several minutes in a summer rainstorm.

8 Slope was calculated based on a straight line between the starting point (immediately prior to the rainfall event) and maximum discharge.

defined as the time between the rainfall centroid (the mid-point of total accumulation) and flow centroid (Maloney and Bennett, 2003). For this same rainfall event, the lag time for Blenkinsop Creek as 1.52 hours, and 2.53 hours for Swan Creek.[9]

The changes in water levels in Swan Lake over the study period are shown in Figure 5.9, between October 2007 and August, 2008. Four fairly marked peaks correspond roughly with the four high flow events apparent in the Swan Creek hydrograph, between November 2007 and February 2008. The approximate level of the lakeshore is also shown,[10] above which point the adjacent wetlands are subject to flooding. Only minor flooding occurred during the study period, whereas during many previous years, large areas of open water have been present outside the boundary of the lake for several months of the year (T. Morrison, pers. comm.).

The hydrograph for the lake has surprisingly acute changes, given the large size of the lake basin and adjacent wetlands. This is likely due to the overall urban character of other inflow discharges (storm drains) in addition to Blenkinsop Creek. Overall, the lake level follows the pattern of precipitation, and the level drops substantially over the summer. Small-scale fluctuations are evident in this graph as short vertical lines, due to evapotranspiration. Examined over one week in July (not shown), a pronounced diurnal pattern is evident, i.e. drawdown during the day due to evapotranspiration, and recharge at night, presumably from surface and groundwater inflow, amounting to nearly 10 cm each day. This pattern is not particularly evident in the discharge in the outflow stream during the same period where discharge was very small (data not shown), therefore the drawdown appears to be due to evapotranspiration and/or lateral flow into the wetlands, and not surface flow losses. This volume of water translates to 9137m^3 transformed to

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9 Note the Swan Creek lag time value is likely an underestimate since there was no clear "end" time to the change in discharge (i.e. a higher stage was maintained rather than a return to the pre-event level), therefore the same time was used as for Blenkinsop Creek, when the peak had subsided.

10 This level was determined from mapping information and calculated from a measurement in the wetland of a surveyed point which was inundated with water (the depth of water was subtracted from the sensor reading for that time). This level is called "approximate" since the shoreline consists of a combination of mats of vegetation and peat deposits that are subject to floating and swelling/contraction.

water vapour during a single day when factored over the surface area of the lake (not including wetland area). As discussed below, this process is important for the effect of climate cooling through latent heat.

In Figure 5.10, a comparison is made between lake levels in Swan Lake and Maltby Lake over the year. Although Maltby Lake exhibits a peak with the early December rain event, similar to Swan Lake, otherwise changes are much more muted, and the water level remains relatively stable over the summer. As stated above, the volume of the two lakes is quite similar, however they differ in other characteristics, particularly the catchment area and elevation. Maltby Lake is not connected with another reservoir upstream by surface water, while Swan Lake is connected with Blenkinsop Lake. As discussed in Chapter 2, the channel connecting Blenkinsop Lake and Swan Lake is man-made, and prior to channelization and draining of the Blenkinsop wetland, Swan Lake had a much smaller catchment area (about half its current size). Also, Maltby Lake has a sizeable linear wetland surrounding its outflow stream, which likely stores a large amount of water for release over the summer. Swan Lake wetland also once extended along Swan Creek as far as McKenzie Ave. Therefore, some of the attributes of these lakes were probably much more similar in the past, and despite some remaining differences (such as elevation and position in the watershed), the hydrograph of Maltby Lake may offer a reasonable representation of the historical hydrograph of Swan Lake. As stated previously, the degree to which either lake interacts with groundwater is unknown, and this could also contribute to some of the differences.

Some water quality parameters of Swan Lake, Prior Lake and Maltby Lake are shown in Figure 5.11. The thermocline for both Swan Lake and Prior Lake was around 2 m, below which point the temperature dropped substantially, from between 20°C and 21°C in the upper layers, to a minimum of around 14°C near the bottom; for Maltby Lake, the thermocline was between 3 and 4m, and a minimum around 7°C was measured in the deepest waters of this lake. In Swan Lake, dissolved oxygen declined steadily from a maximum of 8.1 mg/L near the surface, to 4.36 at 2m. Below this point, dissolved oxygen was near zero. In Prior Lake, dissolved oxygen remained above 5 mg/L until below 3m, where it dropped to less than 1 mg/L. In Maltby Lake, dissolved oxygen remained between 7 and 8 mg/L until a depth of around 5m. Photographs of the three lakes during sampling are shown in Figure 5.12, illustrating the differing aquatic vegetation community. Swan Lake is dominated by algae, duckweed and reed canarygrass, whereas Prior Lake and Maltby Lake have less algae/duckweed and more diverse native aquatic vegetation.

Some of the important points from water quality sampling (data not shown) include the following:

- Secchi depth was very low in Swan Lake (0.58m), moderate in Prior Lake (1.72m) and high in Maltby Lake (4.5m). This indicates a large degree of turbidity in Swan Lake at one extreme, and very clear water in Maltby Lake at the other.
- Electrical conductivity (specific conductance) in Swan Lake was very high, between 448 and 330 µS/cm, throughout the water column. This contrasts with much lower values in Prior Lake (145-151µS/cm), and even lower in Maltby Lake (77µS/cm). This reflects a higher concentration of dissolved ions in the former compared to the latter. Sources of these dissolved substances could include natural weathering, erosion of soils, agricultural runoff, road salt, and bacterial respiration (Water on the Web, 2008).
- Trends for total dissolved solids were similar: 0.24, 0.1 and 0.05 g/L for Swan, Prior and Maltby Lakes respectively. TDS also measures dissolved ions, in addition to non-conductive substances, and potential sources are similar to those listed above for conductivity. Both measures of dissolved substances indicate Swan Lake has values about twice that of Prior Lake, and four times that of Maltby Lake.
- Swan Lake had the highest pH values for surface and near-surface water, while values for all lakes decreased with depth. The high values for Swan Lake are probably due to phytoplankton productivity, and consumption of carbon dioxide.

Oxidation-reduction potential (ORP) is a measure of the likelihood for either chemical reduction (gain of electrons) or oxidation (loss of electrons). The data show Swan Lake has reducing conditions throughout the water column, but particularly in the deeper water layers (with a minimum of -174 mV). At around -200mV (and pH 7), iron reduction occurs, where iron(III) is reduced to the soluble form, iron(II) , and at around -220mV, sulphate reduction occurs (Correll and Weller, 1989). The biological implications of these types of reactions are discussed below. In contrast, ORP in Prior Lake is between 88 and 91 mV, and Maltby Lake has values between 209 and 257 mV, with higher values found in the deeper layers.

Selected parameters of water quality monitoring carried out by Aqua-Tex Scientific Consulting in 2006-2007 (Barraclough and Hegg, unpublished data) are discussed in general terms to characterise the inflow/outflow water quality. Unfortunately, that study did not coincide with the timing of this hydrological study except for a single sampling date, therefore it is not possible to accurately calculate loading rates of contaminants flowing into or out of Swan Lake. Despite the fact that many water quality guidelines depend on concentration of substances only (e.g. mg/L), this value is not as important as loading rates when evaluating impacts on urban aquatic ecosystems (USEPA, 2008a). Loading rates for several parameters for the one date for which flow data is available are summarized in Table 5.4. The discharge in both streams was moderate at this time, which occurred in the midst of typical winter rainfall patterns. Nitrogen loading from Blenkinsop Creek into Swan Lake was occurring at an instantaneous rate of 2.62 kg/h (63 kg/day, assuming constant flow), and phosphorus at a rate of 0.26 kg/h (6.24 kg/day). In Swan Creek, total N loading was 1.69 kg/h (40.6 kg/d) and P loading was 0.28 kg/h (6.72 kg/)d.

The average phosphorus concentration in Blenkinsop Creek over the water sampling period in 2006-2007 (10 samples) was 0.535 mg/L, and all values were well above the aquatic freshwater life guideline of 0.04 ug/L (Barraclough and Hegg, unpublished data). If this value is multiplied by the average discharge over the study period (2007-2008) in Blenkinsop Creek (0.135m^3/s), an annual load (inflow to Swan Lake) of 2.3 tonnes per year is calculated (Table 5.5). A similar calculation yields estimates of P outflow in Swan Creek at 1.8 t/y, and total nitrogen inflow and outflow of 8.3 and 5.2t/y, respectively (Table 5.5). This is a rough calculation, since the water chemistry and flow data did not occur in the same period (except for one sampling date as mentioned). However, it may still give a general idea of the degree of loading occurring. The actual concentration can be expected to vary depending on factors such as antecedent precipitation patterns, season, and activities in the watershed.

Water chemistry within Swan Lake (sampled by the Ministry of Environment in 2002-2003; Kenney, 2003) also shows very high total phosphorus values, ranging from 199 to 1330 ug/L and an average of 0.494 ug/L (n=4, SD=0.558; data not shown). The BC Ministry of Environment recommends criteria for aquatic life between 5 and 15 ug/L, and for recreation a level below 10 ug/L is recommended (Nordin, 1985; BC MoE, 2006), thus the measured values indicate a high degree of nutrient enrichment.

Since many parameters do not have established or recommended criteria, some values are compared to several interior BC lakes (Table 5.6), one of which (Tyhee Lake) is considered mesotrophic to eutrophic (Reavie *et al.*, 2000). The nutrient levels in Swan Lake are an order of magnitude higher than these lakes. Although phosphorus is normally the nutrient of highest concern for freshwater ecosystems, given the proximity to a marine area, the importance of nitrogen loading downstream of Swan Lake should not be overlooked. Although beyond the scope of this study, loading rates from Colquitz Creek into the marine environment, and potential effects on Portage Inlet, merit further investigation.

Sediment quality data for Swan Lake from data collected by Kenny (2003) was compared to available guidelines (CCME, 2002; Wisconsin Dept. Nat. Res., 2003), as well as to mean values for a large number of B.C. lakes, and Beaver Lake (Reiberger, 1992), and is summarized in Appendix E. Swan Lake exceeds some or all these references for total nitrogen (higher than Beaver Lake), aluminum (> BC lakes reference and Beaver Lake); arsenic (>CCME guidelines); calcium (>BC lakes and Beaver Lake); chromium (>CCME and Wisconsin guidelines); copper (>CCME and Wisconsin guidelines); lead (>all references); nickel (>all references) and zinc (>all references).

Finally, as shown in Figure 5.12, the plant community at Swan Lake was dominated by thick algal growth and duckweed (Lemna *spp.*), with a limited diversity of emergent and submersed vegetation. This fits with the water quality data described above, for example low oxygen in deeper water, high turbidity and high pH in the surface water. The species present at Swan Lake are indicative of high-nutrient conditions, and several species that were present in the 1970s and before have disappeared (see Chapter 2 and Chapter 5). Prior Lake has a more diverse vegetation community, algae was not noted, and duckweed growth was more limited. Buckbean (*Menyanthes trifoliata*) (observed at Prior Lake) and marsh cinquefoil *Comarum palustre*) (observed at both Prior Lake and Maltby Lake) are indicative of low to moderate nutrient conditions (McKenzie and Moran, 2004). The water in Prior Lake was relatively clear, although a brownish hue was noted, possibly due to tannins. Maltby Lake had very clear water (Secchi depth was around 4m) and species present were typical of low-nutrient conditions, especially the bog species such as Labrador tea (*Ledum groenlandicum),* bog rosemary *(Andromeda polifolia),* western bog-laurel *(Kalmia microphylla* ssp. *occidentalis),* and round-leaved sundew (*Drosera rotundifolia).* These species were, however, limited to a relatively small area along the shoreline, and other species noted are typical of more moderate nutrient conditions.

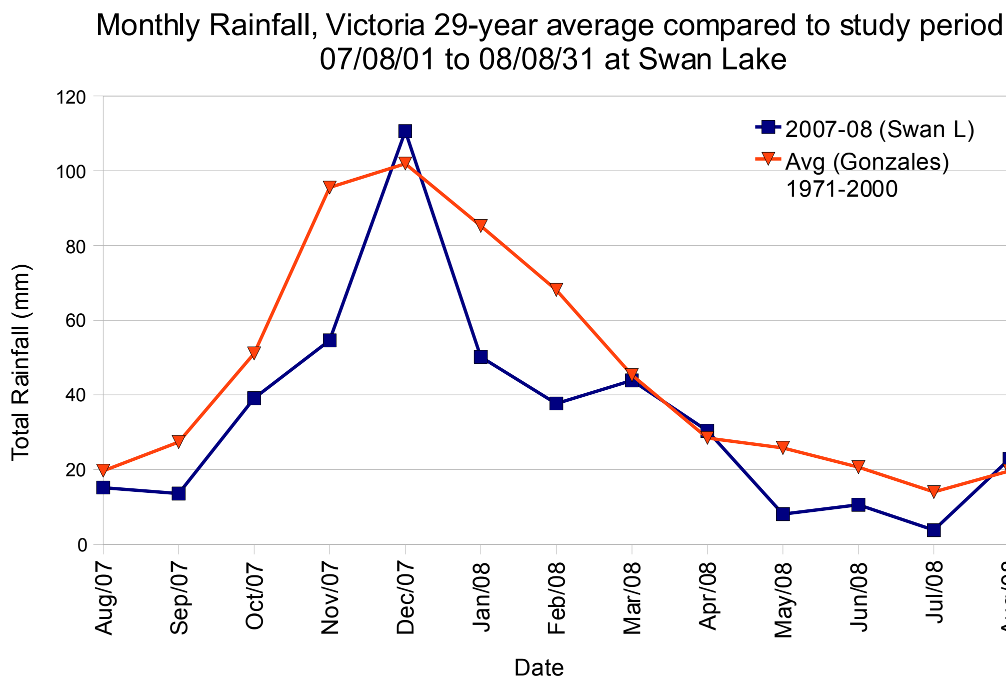


Figure 5.1. Total monthly rain over 13 months, Environment Canada station at Victoria (Gonzales) 29-year average compared to 2007-08 Swan Lake (SL) weather station

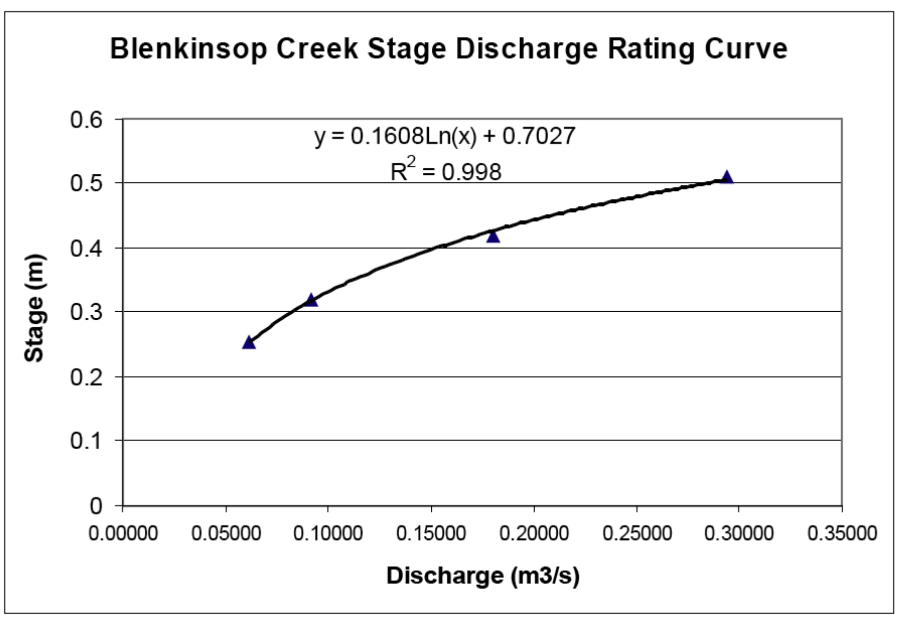


Figure 5.2. Stage-discharge rating curve for Blenkinsop Creek

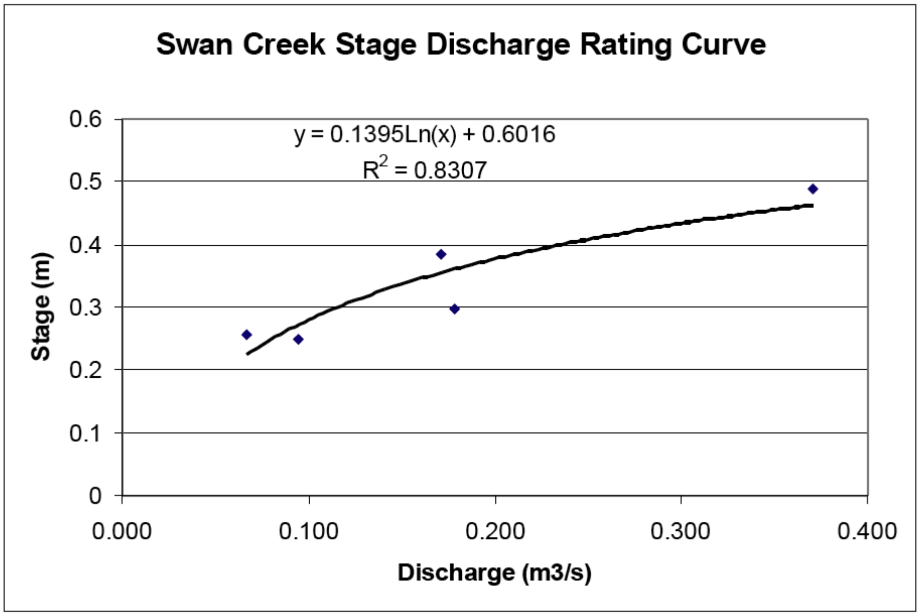


Figure 5.3. Stage discharge rating curve for Swan Creek (high flows, above top of weir)

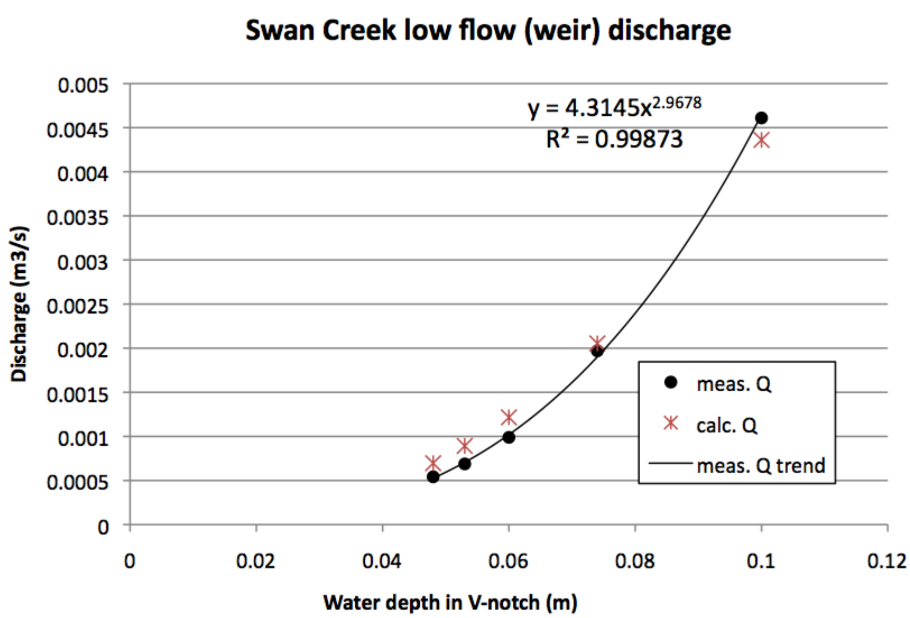


Figure 5.4.Discharge rating curve for Swan Creek low flow, using weir method

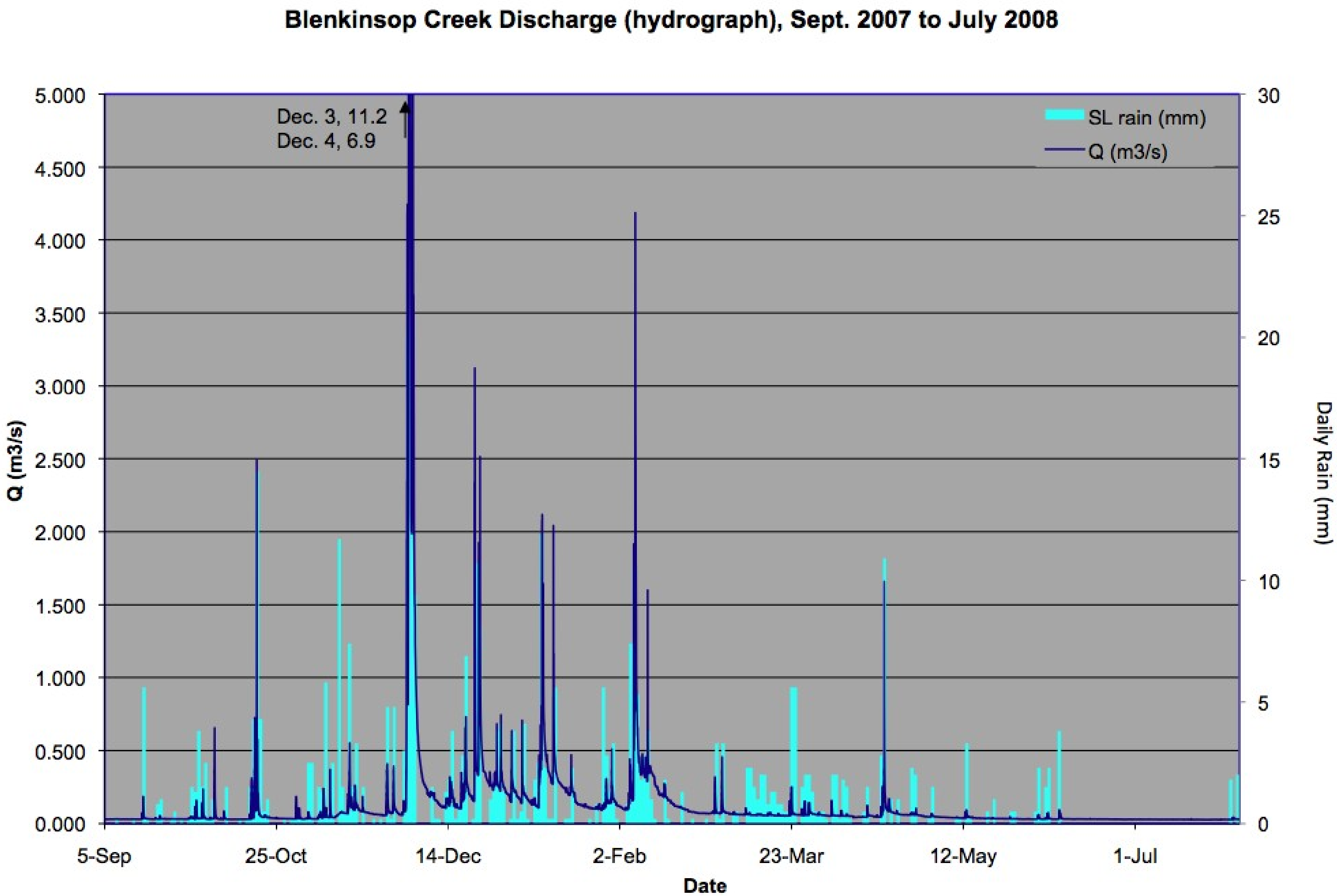


Figure 5.5.Blenkinsop Creek hydrograph, Sept. 5, 2007 to July 31, 2008

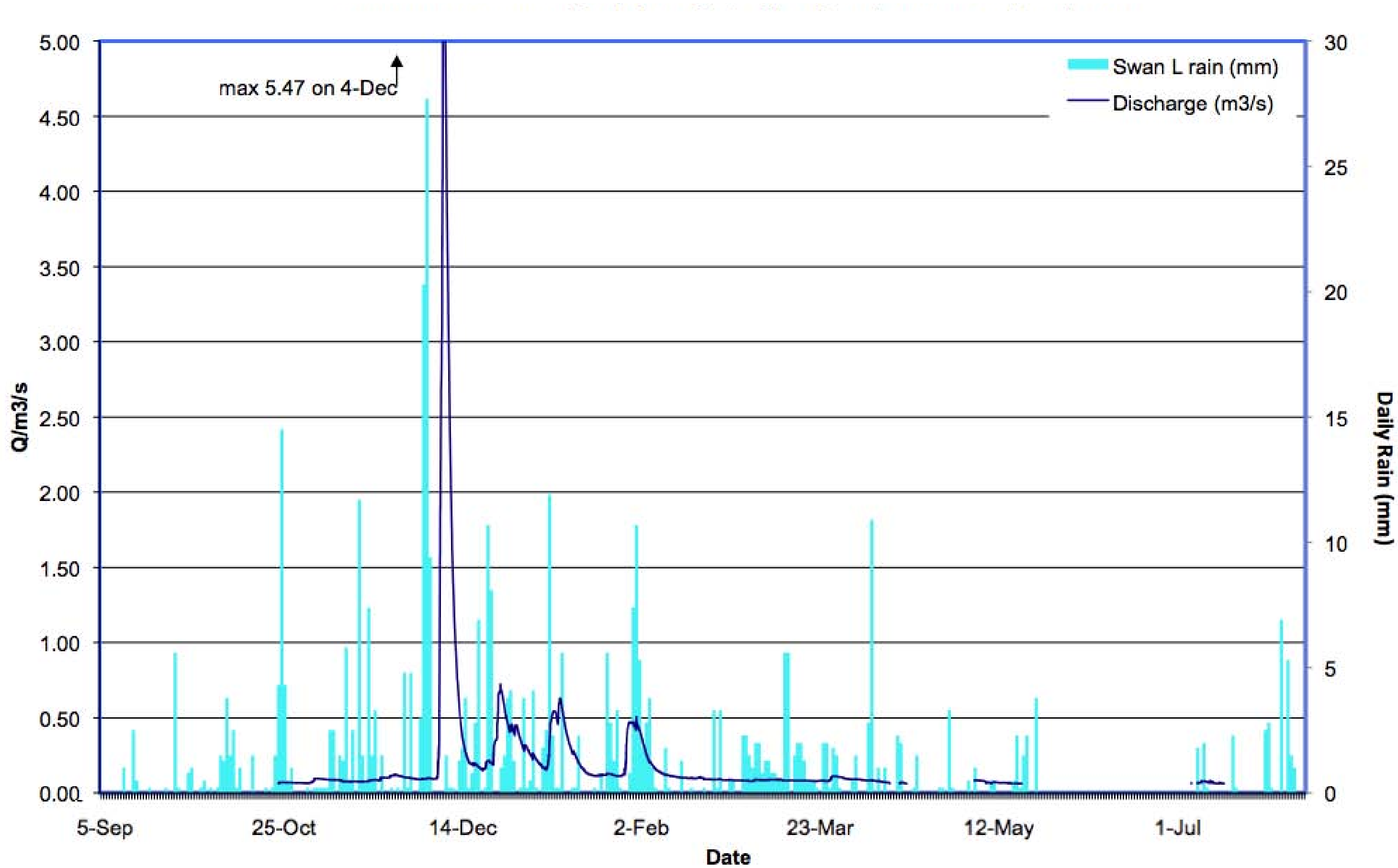


Figure 5.6. Swan Creek hydrograph, August 29, 2007 to Sept. 9, 2008

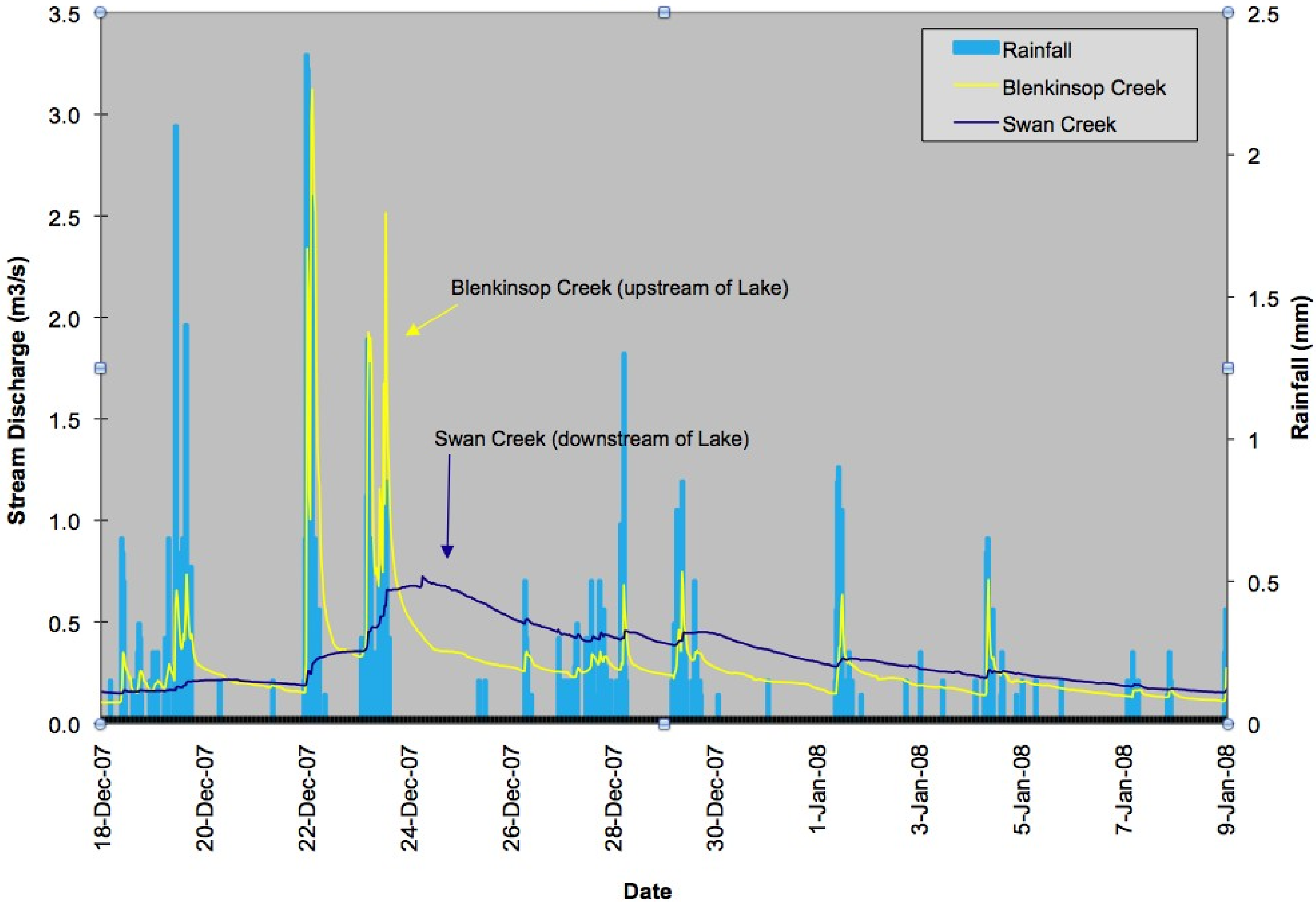
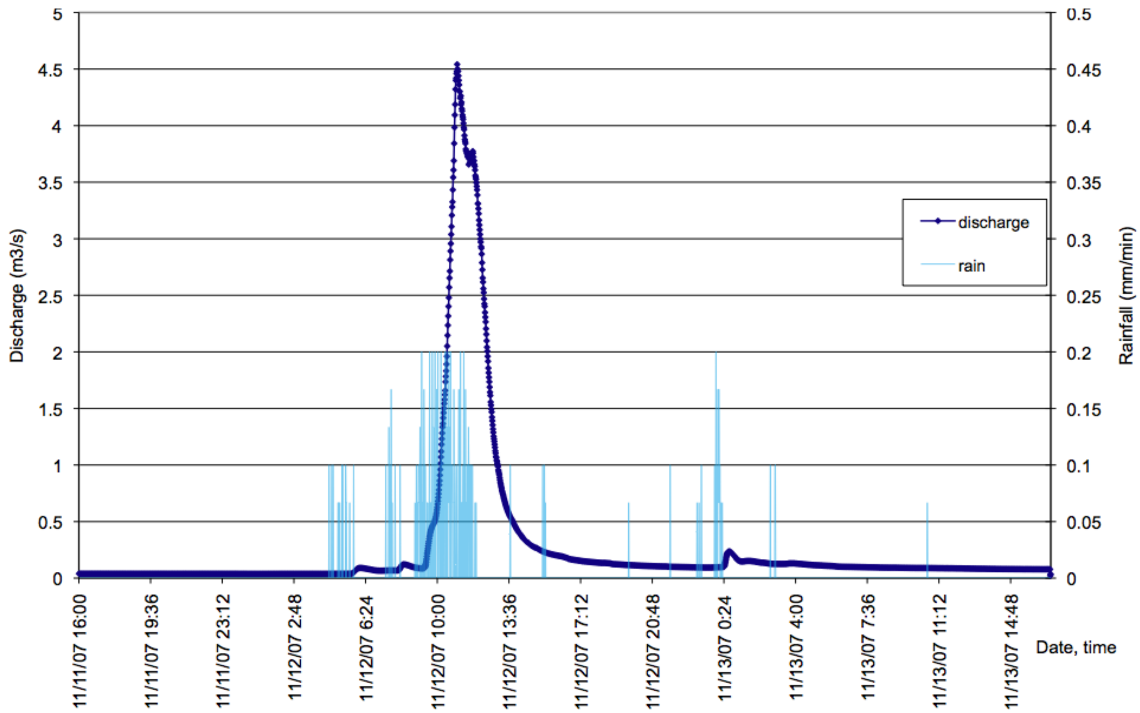


Figure 5.7. Blenkinsop Creek and Swan Creek discharge plotted with rainfall over two weeks, Dec. 18, 2007 to Jan. 9, 2008



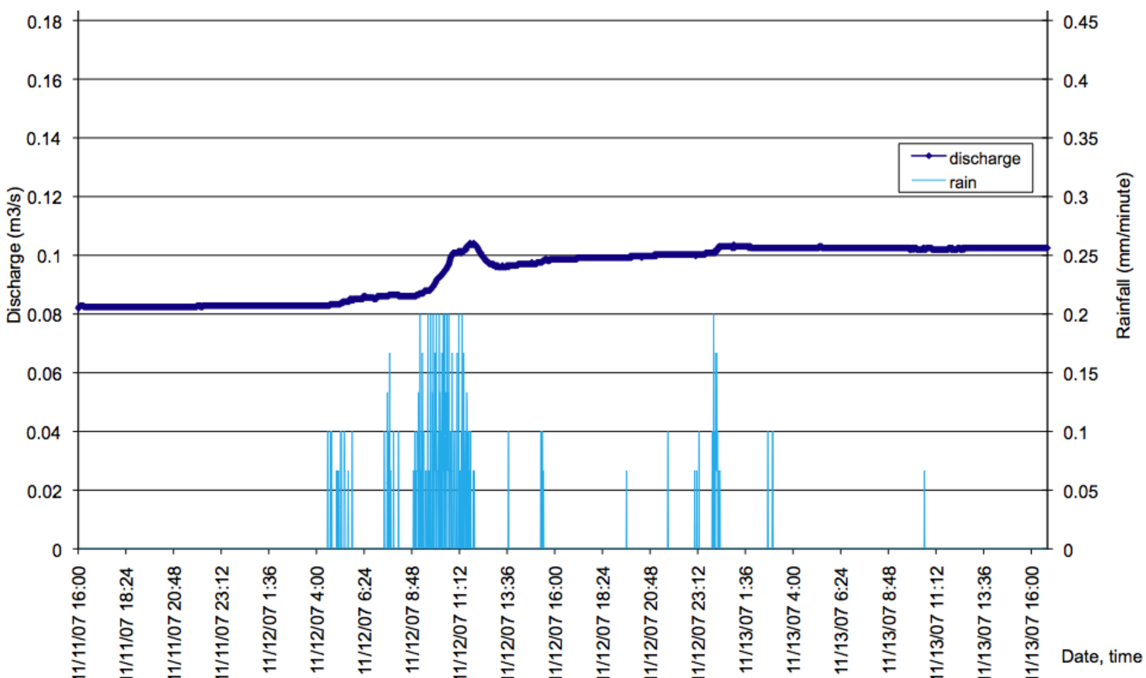


Figure 5.8. Hydrograph for Blenkinsop Creek (top) and Swan Creek (bottom) over a single rain event, logged every minute, November 11-13, 2007; note scale on Swan Creek main (left) y-axis is exaggerated compared to top graph

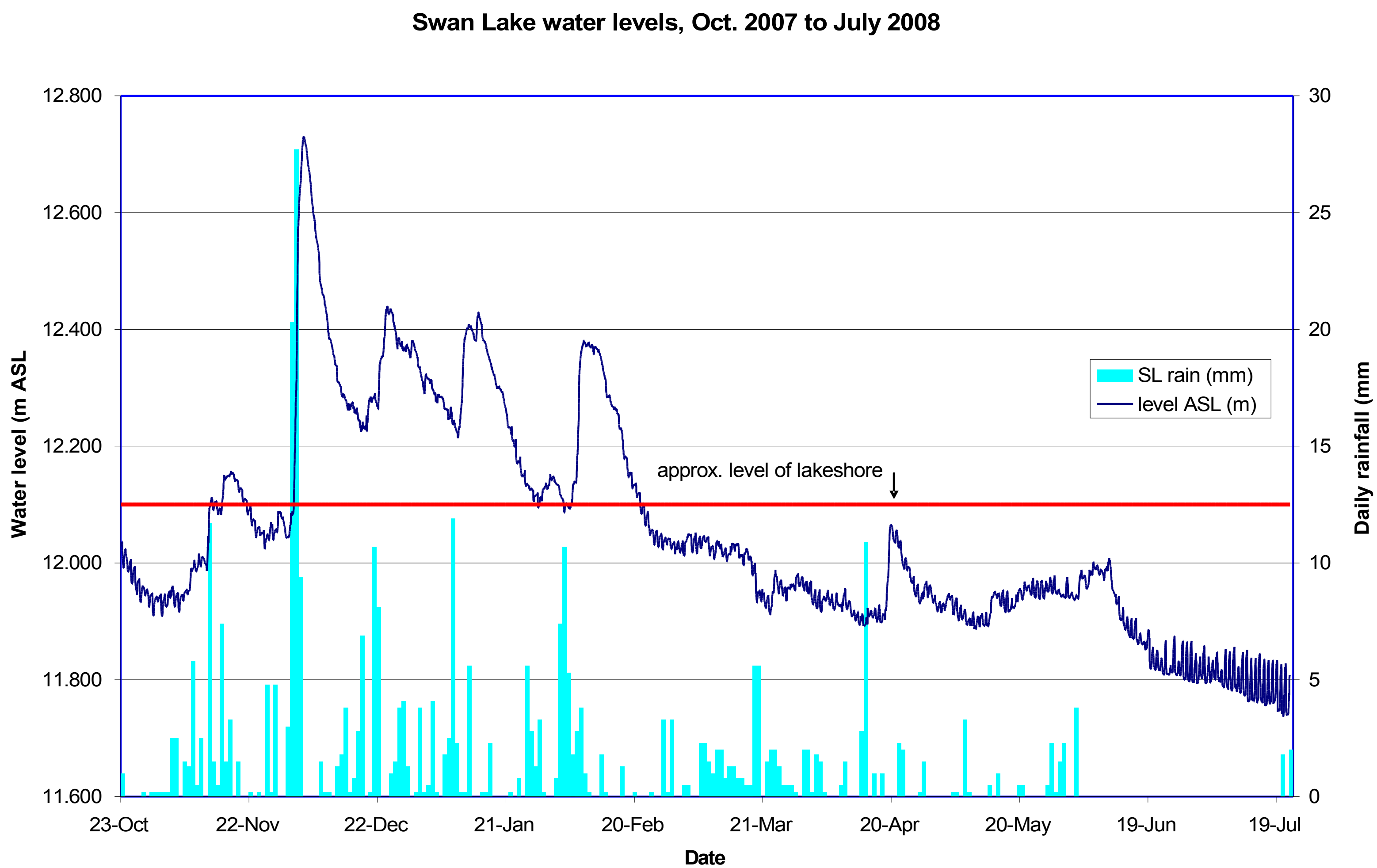


Figure 5.9. Swan Lake water levels, relative to geodetic datum (m above sea level), October 2007 to July 2008

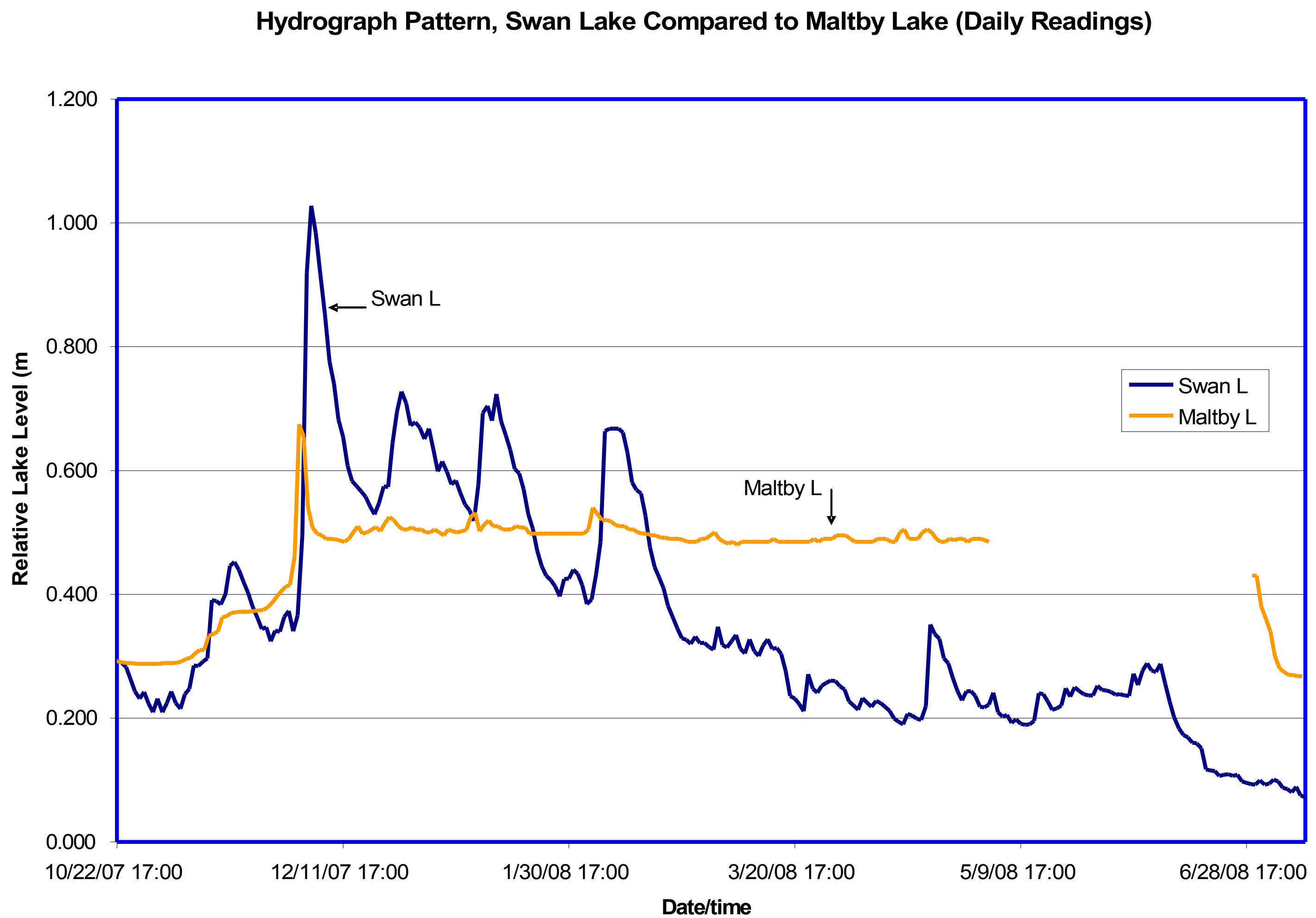
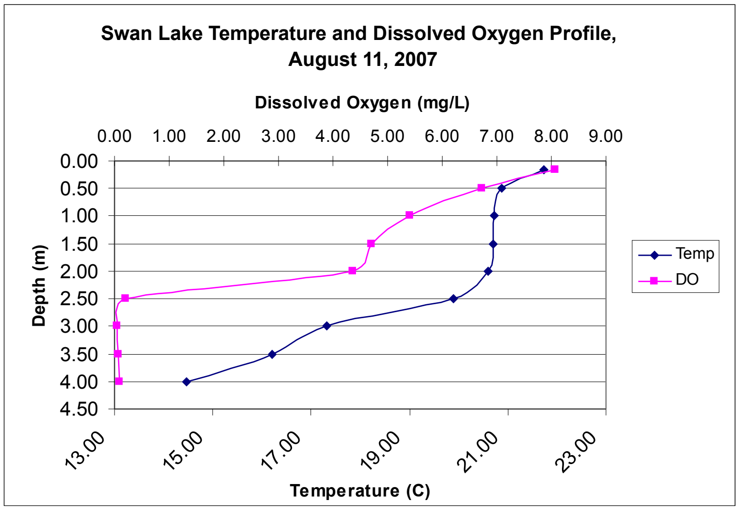
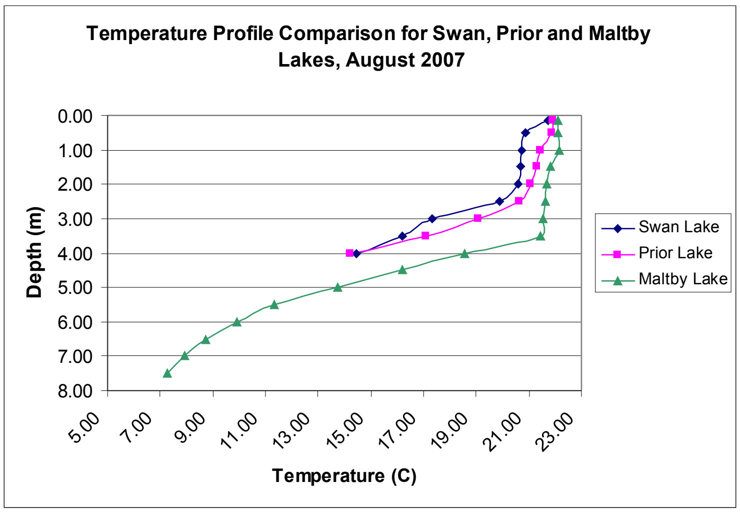


Figure 5.10. Comparison of change in lake levels over the study period, October 2007 to July 2008, Swan Lake and Maltby Lake; daily level readings taken at 1700hrs, starting point set to same.





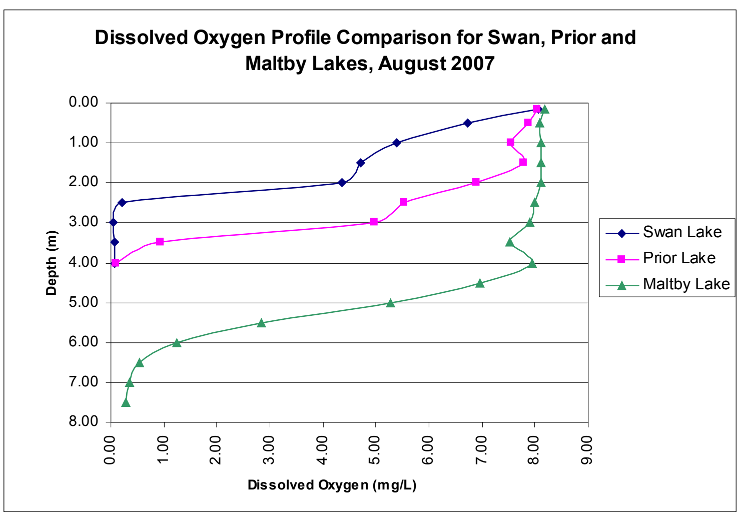


Figure 5.11. Comparison of dissolved oxygen and temperature profiles in 3 lakes

Figure 5.12. Photographs of Swan Lake (top), Prior Lake (middle) and Maltby Lake (bottom) on day of water sampling, August 11 to 13, 2007

Table 5.4. Instantaneous loading rates of selected water quality parameters in Blenkinsop Creek and Swan Creek (Barraclough and Hegg, 2008), calculated using discharge data, December 17, 2007

Location	Date	Time	Q (m3/s)	Q (L/s)
Blenk. Cr.	2007-12-17	1325	0.11	107.9
Swan Cr.	2007-12-17	830	0.14	135.4

			Blenkinsop Creek		Swan Creek	
Parameter	Unit	FWL guideline	Value	Loading (kg/h)	Value	Loading (kg/h)
TN	mg/L		6.76	2.68	3.46	1.69
Al	mg/L	0.1 mg/L	0.48	0.18		
As	ug/L	5 ug/L	1.1	0.43	2.5	0
Ba	mg/L		0.04	0.01		
B	mg/L		0.68	0.26	0.6	0.29
Ca	mg/L		71.9	27.93	49.4	24.08
Fe	mg/L	0.3 mg/L	0.55	0.21	0.06	0.03
Mg	mg/L		19.1	7.42	1.26	0.61
Mn	mg/L		0.07	0.03	0.02	0.01
P	mg/L	0.035 mg/L	0.66	0.26	0.57	0.28
K	mg/L		7.83	3.04	5.6	2.73
Si	mg/L		11.2	4.35	0.13	0.06
Na	mg/L		32.8	12.74	27.5	13.41
Sr	mg/L		0.33	0.13	0.23	0.11
Ti	mg/L		0.01	0		
V	mg/L		0.02	0.01		
Zn	mg/L	0.03 mg/L	0.02	0.01	0.02	0.01
Pb	ug/L		ND	0	0.5	0.24

Table 5.5. Estimated annual nutrient loading from average discharge (2007-2008) and water quality samples (2006-2007), Blenkinsop and Swan Creeks

Parameter	**units**	**Blenk. Cr.**	n	st, dev.	**Swan Cr.**	n	st. dev.
Discharge	m^3/s	0.136	15627	0.45	0.113	18569	0.36
Total P	mg/L	0.54	10	0.25	0.50	10	0.24
P load	kg/year	2316			1782		
Total N	mg/L	1.94	10	1.79	1.46	10	0.82
N load	kg/year	8320			5203		

Table 5.6. Comparison of water quality values in Swan Lake and four interior lakes (Reavie et al., 2000)

	Swan L.	Takysie L.	Tchesinkut L.	Francois L.	Tyhee L.
Surface area (km2)	0.9	5.1	33.8	258	3.2
Total P (ug/L)	199 to 1330	22 to 130	4 to 8	6 to 10	12 to 53
Total N (ug/L)	3120 to 5940	920 to 1200	200	250 to 320	550 to 610
Conductivity (uS/cm)	330	150 to 168	135 to 136	84 to 93	364 to 369
pH	8.0 to 8.48	7.1 to 7.9	7.91 to 8.08	7.63 to 7.80	-
Total Ca (mg/L)	25.6 to 51.8	16-18	17	9.5 to 11.0	-
Total Mg (mg/L)	10.4 to 14.8	5.7 to 6.0	4.4	2.5 to 2.9	-
Colour	60 to 80	35 to 55	5	9 to 15	-

** NB: Swan Lake TP, TN, Ca, Mg and colour sampled by Kenny (2003); conductivity and pH sampled by L. Townsend in 2007*

5.4. Discussion

5.4.1. Stream Channels and Relationship to Hydrographs

Blenkinsop Creek and Swan Creek were assessed qualitatively in Chapter 3. In the reaches immediately adjacent to Swan Lake, the streams were both found to be "nonfunctional," but for different reasons. Blenkinsop Creek exhibited channel incision, over-steepened banks and a lack of channel complexity, thought to be due to "flashy" flows from urban surfaces of the watershed (as well as to historic channelization). The reach of Swan Creek downstream from Swan Lake is a historic wetland in a nearly flat area that has been drained via a ditch; flows are attenuated by the lake and wetlands, but riparian vegetation is absent due to land use (allotment gardens). This study adds to these findings with quantitative (graphical) analysis of flows through the Swan Lake system.

The response of flows in Blenkinsop Creek to rainfall is rapid, as shown with the example of the high-resolution data for a small magnitude event in November, resulting in a steep slope of the rising limb of the hydrograph, and a short lag time (Figure 5.8). A large number of short-duration peaks were observed throughout the year, particularly in winter, sometimes in response to relatively small rainfall events (Figure 5.2). This reflects a lack of floodplain storage in the incised and dug-out channel throughout most of its length, and the effects of culverted sections in accelerating flows. Also, the source area for the stream has been expanded: in a natural watershed, the area around the stream channels that contributes subsurface or surface flow contracts in the dry summer, and expands in the wet winter (Naiman *et al*., 1992). In an urban setting, impervious road surfaces and storm drains link otherwise distant portions of the watershed such that they contribute flows during all times of the year, even in small precipitation events. As discussed in the following chapter, this over-connection in the system may represent a source of decreased resilience, since small perturbations (e.g. nutrient or pollution inputs) quickly resonate through the system and are transmitted downstream, instead of being muted locally. Some baseflow is maintained throughout the summer, due to the connection with Blenkinsop Lake, as shown in the hydrograph. However, this flow probably does not benefit the water quality in Swan Lake very much since Blenkinsop Lake is also a highly eutrophic lake (Barraclough and Hegg, 2008).

In Swan Creek, several fairly sharp peaks were evident in the largest rainfall events of the year, but these were not as rapid nor as large as those in Blenkinsop Creek, and smaller events were difficult to discern in the data (Figure 5.6, Figure 5.7 and Figure 5.8). At the gauging station, the flow data are influenced more by the lake and wetlands and therefore are not typical of an urban stream. Thus Swan Creek in this location is not subject to the same magnitude and frequency of erosive flows as Blenkinsop Creek. However, apart from stagnant water in the stream channel, little summer storage is achieved due to adjacent land use as community gardens, and past channel dredging that disconnected the stream from its floodplain; low flows in mid-summer approach zero (data not shown). This drop in flow represents less supply to downstream portions of the system, except where they are locally replenished (e.g. from smaller tributaries, runoff from lawn irrigation, etc.).

North of McKenzie Ave. (downstream from the gauging station), a constructed wetland and channel complex was created in 2001 that also accepts runoff from adjacent developments (Malmkvist, 2002). This system likely releases some summer flow and attenuates the energy of winter flows. Although much of Swan Creek is degraded due to past dredging, trampling, erosion and invasive species, it also includes areas with accessible floodplain that could be fairly easily rehabilitated (Chapter 3).

Since Swan Creek is not subject to highly erosive flows, as shown in the hydrograph, especially compared to the much flashier Blenkinsop Creek, stream channel restoration using "soft engineering" techniques (e.g. riparian plantings, bank re-configuration and large wood) has a reasonable chance of success. If water quality can be improved, this stream would be an excellent candidate for restoration of salmon spawning habitat, for example in some reaches downstream from the constructed wetland in the Willowbrook subdivision. The restoration target in the upper section of Swan Creek, between the Patricia Bay Highway and McKenzie Ave., should be a wetland of some form, to fit with the topography and flow regime (as well as the historical condition), and provide filtration, nutrient uptake and hydrological storage.

5.4.2. Swan Lake Hydrograph

The water levels in Swan Lake were variable over the study period, with large peaks occurring during winter rainstorms (Figure 5.9), even though rainfall was well below the average during the study period (Figure 5.1). This is probably due to: 1) a large catchment area; 2) a large amount of impervious surfaces in the watershed, and little mitigation of stormwater runoff; and 3) high connectivity due to storm drains and agricultural ditches. Drawdown occurred throughout the summer, but tapered off in late summer, when large diurnal fluctuations were evident due to evapotranspiration. Some degree of the drawdown is probably due to deliberate drainage effected in Swan Creek, to allow for agriculture and urban development (see Chapter 2). The pre-development hydrograph pattern probably had smaller peaks, since less surface runoff would have occurred. Higher water levels were probably also maintained in summer, since more water would have been stored/released from the linear wetland surrounding the outflow stream, as well as from wetlands immediately adjacent to the lake.

Water loss through evapotranspiration, and/or lateral transfer to adjacent wetlands, amounted to around 10cm of lake level change between day and night, during mid July (data not shown). This was calculated to represent a volume of over 9000m^3 per day just from the lake surface. This process likely has a substantial effect on the local energy budget, i.e. ratio of sensible to latent heat or Bowen ratio.[11] As it requires 2.45 MJ of energy to evaporate one litre of water (at 20°C; Eamus *et al.*, 2006), and assuming all 9000 m^3 of water are evaporated, this process requires 22,050 MJ or 22 GJ of energy that would otherwise contribute to an increase in temperature, if the lake was not present, over one day. Expressed another way, this energy is equivalent to one tonne of coal (23GJ/t; United States Oil from Coal, no date)[12]. Over the several weeks or more of summer weather conducive to this amount of evapotranspiration, this amounts to a substantial cooling function of the local climate. Conversely, this service has been lost where previously existing wetlands have been drained, notably the large area south of Blenkinsop Lake and the linear wetland previously located along Swan Creek near Swan Lake. While Victoria may not be particularly prone to heat waves, air conditioning in commercial and institutional buildings still probably represents a large portion of operation and maintenance budgets, and the population in temperate climates may still be vulnerable, since few people are prepared for extreme heat. As discussed in more detail in Chapter 6, evapotranspiration by vegetation and water retained on the landscape helps to confer ecological resilience, since solar energy is dissipated, supporting other biophysical processes important for maintaining ecosystem function. Detailed micro-meteorological studies would be useful to quantify such effects.

Since there are no gauged lakes in the nearby area that could serve as a reference site for comparison with Swan Lake's hydrograph, I studied the patterns in Maltby Lake using daily staff gauge readings. Maltby Lake is located in a largely undeveloped watershed, but has some important differences, such as a much smaller catchment area, and a relatively higher position in the watershed (as well as higher absolute elevation).

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11 Evaporation of water transforms solar energy into latent heat that absorbs heat from the surroundings and therefore does not cause a rise in temperature; in contrast, when solar radiation is received on a dry land surface, it is transformed to sensible heat, which is felt as a change in temperature (Pokorný, 2001). Thus the loss of water from the landscape, for example through wetland drainage and removal of vegetation, is a major contributor to urban heat island (Grimmond and Oke, 1999).

12 Assumes burned in a coal-fired power plant at 38% thermal efficiency.

Therefore the comparison cannot be taken too far, yet it may offer a reasonable approximation of pre-disturbance characteristics of water level fluctuations in Swan Lake, as described previously. The water level fluctuations in Maltby Lake are very slight compared to Swan Lake, and appear to have been maintained at a relatively higher stage over the summer[13] (Figure 5.10). This may be due to more hydrological storage in the outflow stream wetland, although there could also be groundwater inflows that were not quantified in this study. As discussed in Chapter 4, a number of previously known wetland plant species at Swan Lake have been extirpated; the marked (and possibly excessive) water level fluctuations could be a contributing factor to their loss, likely in addition to poor water quality. For example, invasive reed canarygrass (*Phalaris arundinacea*), which now dominates large areas of the wetlands, tolerates a wide degree of soil moisture conditions (Kercher and Zedler, 2004), whereas other native species could be more sensitive to such changes, creating conditions favourable for reed canarygrass invasion. On the other hand, certain wetlands (e.g. prairie potholes and coastal lake marshes) depend on natural water level fluctuations to maintain biodiversity and complex habitats, and when they are subject to too much control, undergo homogenization and increased invasion by non-native species (Middleton, 1999; Van der Valk and Davis, 1978; Bortoluzzi, pers. comm). Therefore, in the long term, ecological resilience as it relates to Swan Lake water levels may be conferred by restoring some degree of natural water level fluctuations. This could involve intercepting and infiltrating/evapo-transpiring rainwater throughout the watershed to reduce peak flows, and restoring the outflow wetland to support water levels in the summer. This would "dampen" current fluctuations but still allow for natural drawdown and flooding, and may help to create more favourable conditions for native aquatic and wetland vegetation and fauna. However, there is also the problem of high nutrient levels in the lake, which could be partially alleviated with increased flushing (with high-quality water) in the short to medium term; this is discussed further in Chapter 6.

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13 Unfortunately, some readings were missed over part of the summer, due to illness on the part of the volunteer taking the readings.

5.4.3. Water Quality

The water quality parameters show that Swan Lake is a highly turbid shallow lake subject to elevated nutrient levels in the water and sediment, where microbial decomposition of organic matter at the sediment-water interface leads to negligible levels of dissolved oxygen in the lower half of the water column.[14] Cyanobacterial blooms are common, diversity of aquatic vegetation is low and submersed species are uncommon. In comparison, Prior Lake appears to be a moderately rich (mesotrophic) lake with a similar depth and temperature profile, but higher dissolved oxygen, greater water clarity, and more diverse vegetation, including submersed species such as *Potamogeton*. Maltby Lake is an oligotrophic to mesotrophic lake, and is the deepest of the three lakes at 8m. The water in Maltby Lake is very clear and is cool at the lowest depths, has high dissolved oxygen to a depth of about 4m, and diverse aquatic vegetation species are present. These conditions are also favourable to fish, and Maltby Lake supports cutthroat trout, among others (the fish present in Prior Lake are not known). Swan Lake consists of an inhospitable environment for salmonid fish species for most of the year, and the degraded water quality is maintained by internal and external processes, such as ongoing nutrient inputs, recycling of phosphorus from sediments and inputs of dissolved substances from the watershed, as shown with water quality sampling and as inferred from anoxic and reducing conditions in the hypolimnion.

Water chemistry combined with flow data for a single date showed very high loading rates of nutrients and dissolved substances. For a single sampling date in winter, total nitrogen loading was calculated at 6.24 kg/day in Blenkinsop Creek and 3.46 kg/d in Swan Creek. Phosphorus loading was calculated at 6.24 kg/day in Blenkinsop Creek, and 6.72 kg/day in Swan Creek. For comparison, Naiman *et al.* (1992) reported annual phosphorus budgets for four forested coastal watersheds ranging from 0.1 kg/ha/yr to -0.3 kg/ha/yr, and mean annual P concentrations typically less than 0.06 mg/L.

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14 Although this study entailed only a single sampling date, results are consistent with other studies (e.g. Kenney, 2003) and anecdotal evidence such as observations of algal blooms over several decades (T. Morrison, pers. comm.).

In terms of nutrient loading to Swan Lake, the Blenkinsop Creek P values are most important, due to the importance of P in eutrophication of Swan Lake, for short-term loading and long-term recycling from the sediments. The P loading into Swan Lake from Blenkinsop Creek over a year was coarsely estimated at 2.3 tonnes, using 2006-2007 water chemistry and 2007-2008 flow data (Table 5.5).[15] This estimate does not include other likely and known sources of phosphorus, for example a tributary stream just downstream of the Blenkinsop sampling/gauging site that showed very high concentrations of P (Barraclough and Hegg, 2008), and other stormwater outfalls also probably contain relatively high nutrients from residential and road runoff. In Swan Creek, the nitrogen loading is more important for eutrophication of the marine environment; although assessment of this effect was beyond the scope of this study, total N loading was coarsely estimated at 5.2 tonnes per year. The implications of nutrient loading for ecological resilience are discussed in more detail in the following chapter. Comparing the three lakes, and drawing on other comparisons from the literature, permits the conditions in Swan Lake to be contrasted with less disturbed aquatic systems. Since Prior Lake has a similar depth and temperature profile, its water quality criteria are probably the most realistic as restoration objectives for Swan Lake.

The sediment in Swan Lake appears to be highly organic, and contains high nitrogen content; the phosphorus concentration of the sediment (1704 ug/g) could not be compared with a guideline or reference, but is assumed to be high. Several heavy metals are present in amounts exceeding the guidelines and/or comparisons, notably lead, nickel and zinc (Appendix E). The most likely source of these metals is automobiles and road runoff, however other sources could include buried refuse (e.g. in an old dump site in the wetland near the nature house), atmospheric deposition and toxic spills from the watershed. The phosphorus content should be better evaluated or compared with a suitable reference site to more accurately model the yearly loading rate, in order to identify targets for reduction, and possible mitigation strategies (e.g. Carpenter, 2005).

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15 The mean P concentration in Swan Creek from 10 samples taken in 2006 to 2007 was 0.50 mg/L for Blenkinsop Creek and for 0.54 mg/L for Swan Creek (Table 5.5; Appendix E).

Water sampling carried out over 2006 and 2007 (Barraclough and Hegg, unpublished data) shows that Blenkinsop Creek exceeded guidelines for aquatic life (either consistently or occasionally), for nitrite nitrogen, aluminum, chromium, iron, mercury, phosphorus, lead and zinc. Similarly, Swan Creek exceeds guidelines for aluminum, iron, mercury, phosphorus and lead.

Some reduction of certain contaminants appears to occur in the lake, between the inflow and outflow, however this is difficult to properly assess given the intervening inflow sources between sampling points. There are a number of potential nutrient sources in the watershed. Agriculture is a prime suspect; food crops as well as a turf farm are cultivated in the Blenkinsop Valley. Golf courses (two of which are located in the watershed) and residential and commercial landscaping could also contribute fertiliser run-off.

Both streams were also frequently below the dissolved oxygen guideline for aquatic life (greater than or equal to 6.5 ppm; BC Ministry of Environment, 2006), at many sampling locations throughout the study (Barraclough and Hegg, unpublished data). This is important for species intolerant of anoxic conditions, such as salmonids and their prey.

Blenkinsop Creek, and to a lesser degree, Swan Creek, frequently transports large loads of dissolved substances, as shown with high measurements of turbidity, conductivity and the elevated concentration (in both water and sediment) of cations such as sodium, calcium, magnesium and potassium. In a “healthy” watershed with similar geology and climate, these substances would be retained in the soils and would contribute to productivity of the landscape, in terms of either native forest vegetation or agricultural crops. Their loss represents a loss of value from the land (i.e. fertility), and once in freshwater or marine receiving environments, contributes to degraded water quality (Ripl and Hildmann, 2000). The levels of dissolved substances leaving a watershed therefore represent a possible metric for landscape “health” and resilience that also links with exergy concepts, as discussed in the following chapter.

In summary, the water quality data indicate that Swan Lake is still in a state of “cultural hyper-eutrophication,” much as it was in 1975 and before (Zaccarelli, 1975). Although point-source nutrient loading has for the most part ceased, non-point source nutrient loading continues, and has probably worsened with increased development and more intensive agriculture in recent decades. The main suspected source of nutrients are fertilisers used in agriculture and residential landscaping. One of the large farms in the Blenkinsop Valley, Galey Farms, has recently nearly eliminated chemical pesticide use, and water quality in Blenkinsop Creek on that property has improved since restoration of a section of the stream (Barraclough and Hegg, 2008; Aqua-Tex Scientific, pers. comm.). However sub-surface drainage of the former wetlands in the Blenkinsop area and other cultivation practices (e.g. the turf farm) likely continue to release a large amount of nutrients.

Phosphorus recycling from sediments in Swan Lake is very likely, as indicated by the strong reducing conditions, low oxygen, and high P in the lake water and sediment. The historic legacy of intense nutrient loading is therefore probably still influencing the function of the lake. Thus Swan Lake resides firmly in the “turbid water state” and due to ongoing nutrient inputs it will likely be very resistant to attempts to shift it back to a state with clear water (Carpenter and Cottingham, 1997; Scheffer, 2004). Prior to initiating any lake-specific treatments to alleviate eutrophication, it is important to reduce inputs from upstream soil and fertiliser sources. Strategies can include incentives for preserving buffers along agricultural ditches and riparian areas, education for farmers and residential landowners about effects of fertiliser and other chemical use on aquatic ecosystems, and municipal management of surface runoff to effect filtration and purification of surface flows.

Conclusions

The study hypothesis was supported, in that hydrological monitoring showed clear indications of the effects of urbanisation. Specifically, discharge in Blenkinsop Lake, and lake levels in Swan Lake, where shown to be highly “flashy,” reflecting a large amount of impervious surfaces and culverts in the watershed, little interception or retention of surface flows from urban areas, and historic land use effects including wetland drainage and conversion of streams to straight ditches. Surprisingly, Swan Creek exhibited a much more attenuated hydrograph due to the buffering effect of Swan Lake and its wetlands.

This analysis helps to show the dramatically different conditions in the two streams, highlighting greater opportunities for restoration in Swan Creek. Drawdown in Swan Lake over the summer was also surprisingly marked compared with Maltby Lake. This is thought to be due in large part to the loss of storage in floodplain wetlands along Swan Creek. The hydrological study was also useful for meaningful water quality analysis, i.e. estimation of loading rates of various nutrients and pollutants, and revealed further indications of deleterious effects of urbanisation. Comparison with two reference lakes was useful since it is difficult to assess many parameters and patterns without a comparison with a local site subject to similar weather disturbances. Ongoing hydrological monitoring of the sites established in this study, coupled with water quality studies, is highly recommended, to generate more detailed information important to the management of this area.

With respect to the relevance of hydrology to ecological resilience, there may be potential indicators to link these two bodies of research, however longer term data is required, as discussed in the following chapter.

This study constitutes the first comprehensive (although data-limited) study of watershed scale processes affecting Swan Lake, and highlights the need for both restoration and further study and monitoring. Traditionally, management in urban areas has relied on the assumption that water resources can be controlled through technology and policy-based approaches, often in reaction to a particular crisis such as flooding or human health-threatening pollution (Paul and Meyer, 2001; Zalewski *et al.*, 2003). However, as complex social-ecological systems, watersheds do not respond favourably to "over-engineering," whereupon ecosystem services are often degraded further, leading to reduced resilience to disturbances such as high rainfall events and pollution. Restoration should focus on reducing the "flashiness" of the hydrograph (indices of flashiness are briefly discussed in the following chapter), mimicking the pre-development hydrological regime, as well as improving water quality. Strategies to accomplish these objectives are discussed in Chapter 6.

Chapter 6. Synthesis: Past and Present Ecological Resilience of Swan Lake Watershed

In this chapter, a discussion of the resilience of components of the watershed is followed by potential indices of overall watershed health and resilience, based on the findings from previous chapters. In Chapter 1 (p. 19), ecological resilience was defined as the ability of a system to absorb disturbances and provide ecosystem services without shifting to an undesired stable state, and without requiring excessive resource and energy input. A novel definition of ecological health is proposed below in this chapter, and an assessment framework is then provided, followed by recommendations for improving watershed health and resilience.

6.1. Resilience and Alternative States in Swan Lake Watershed Ecosystems

Systems Models

In order to increase understanding of complex systems, systems models are increasingly promoted and applied to represent feedbacks and interactions among key variables and processes (e.g. Allen *et al.*, 2005; Bennett *et al.*, 2005; Cumming and Collier, 2005; Janssen *et al.,* 2006; Resilience Alliance, 2007a, 2007b). For example, Bennett *et al.* (2005) recommend a series of questions to identify system components; this approach was used here to help illustrate current understanding of ecosystem processes in Swan Lake watershed. Selected questions from this process are shown in Table 6.1, and supporting discussion for this table is provided in the sections below (the full complement of questions addressed is provided in Appendix F).[1] From this analysis, a few simple models can be drawn showing positive and negative feedback loops[2] that help to maintain various stable states. These models are intended to illustrate only some of the key processes, and are necessarily simplified compared to the full range of interactions occurring in a given system.

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1 Note that an interdisciplinary process is usually recommended to arrive at the models, an approach not possible in the scope of this study, therefore the stated system characteristics should be seen as estimated qualities that ideally should be subject to more detailed analysis.

2 A positive feedback loop amplifies a particular process, whereas a negative feedback loops dampens it (Bennett *et al.,* 2005).

Table 6.1. Selected questions relating ecological resilience to components of Swan Lake watershed*

	Lakes	**Streams**	**Wetland (S.L.)**	**Uplands**
What aspect of the system should be resilient?	Water quality	Biophysical conditions, water quality	Native vegetation community	Vegetation cover and evapo-transpiration
What kind(s) of change would we like the system to be resilient to?	Agriculture, urban development	High flow events; development in watershed	Invasive species	Development and human pop. growth
What (if anything) moves the system from being controlled by one feedback loop to another?	O2 content of water; level of P loading	increase in EIA, decrease in water quality	clearing and disturbance; ongoing fluct. in water levels, sediment, nutrients	Patterns of land development req'ing large-scale clearing and minimal replanting
As indicated by the feedback loops, what is the threshold value of the state variable?	P conc. when P recycling becomes signif.	amount of EIA when degraded cond's become significant	Amount of shrub clearing before grass dominates	Amt. of disturbance that causes significant ecol. degradation
How far is the state variable from the threshold value?	est. to be far exceeded	varies by stream/reach (see PFC assmt)	est. to be far exceeded	est. to be far exceeded
How fast is the state variable moving toward or away from the threshold?	away (on turbid side) at slow to moderate rate	away (on degraded side) at slow rate due to cohesive soils	may be static or slowly moving back toward threshold	est. to be moving moderately fast toward further degradation
How do outside shocks/controls affect the state variable and how likely are those shocks/controls?	More extreme rainfall events could incr. loading	climate change may cause more extreme runoff events; increased urban devel. likely	sediment & nutrient loading favour grass dominated state	economic crisis, peak oil, climate chg may all worsen effects
What is current state of the system?	Algae-dominated	Degraded (non-functional and poor water qual)	grass-dominated	urban barrens
Is current state desired or undesired?	undesired	undesired	undesired	undesired
What is estimated stage or point in the adaptive renewal cycle?	K	K	r to K	K

*Based on Bennett et al. (2005). Abbreviations: S.L. (Swan Lake); P (phosphorus); EIA (effective impervious area); fluct. (fluctuations); req'ing (requiring); ecol. (ecological); est. (estimated); PFC (Proper Functioning Condition); assmt (assessment); qual (quality)

Terrestrial Ecosystems

Prior to large-scale land clearing and development in Swan Lake watershed, the terrestrial ecosystems consisted of a mixture of coniferous forest, open grassland, Garry oak woodland and transition ecosystems at various stages of succession, maintained in part by indigenous burning (Nuszdorfer *et al.,* 1991; Turner and Peacock, 2005; Storm, 2002; McDadi and Hebda, 2008). A “climax” community, in the Clementsian sense, therefore probably did not exist. This is relevant today, for example for defining restoration goals.

Fire effects on terrestrial ecosystems also have important feedbacks with aquatic and riparian ecosystems. Much of the fire ecology literature focuses on the "damage" caused by large-scale fires, for example increased erosion, sedimentation and mass wasting (e.g. Elliott and Vose, 2006). In contrast, indigenous burning such as it was practised in the Pacific Northwest usually consisted of frequent low-intensity fires that were carried out in summer (Turner, 1999; Boyd, 1999b), when soil loss would have been limited due to the very low rainfall received in summer months in the area (Environment Canada, 2008). Furthermore, fire can have beneficial effects on ecosystem function, for example: sediment and large wood delivered to stream channels provides critical habitat and structure (Miller *et al.*, 2003; Naiman *et al.*, 1992; Prichard, 1998); many riparian vegetation species respond favourably to fire disturbance (Dwire and Kauffman, 2003; Lake, 2007); and nutrients are released and delivered to streams, resulting in pulses of primary productivity that benefit many aquatic and marine species (Barsh, 2003; Elliott and Vose, 2006). These processes would have been active in Swan Lake watershed to some degree. Furthermore, a more open tree canopy and grasslands, products of natural and anthropogenic fires, likely decreased evapotranspiration, increasing year-round stream flow (e.g. Meixner and Wohlgemuth, 2003), with potential effects on fisheries. In short, fires are part of the natural disturbance regime of both forests and freshwater/marine ecosystems that helps to maintain ecosystem resilience (Bisson *et al*., 2003; Dwire and Kauffman, 2003; Holling, 1986). Consequently, fire suppression, and transformation of the landscape as described below, constitutes one of many alterations to ecosystem processes in the study area.

Today, the native terrestrial ecosystems in Swan Lake watershed have been practically erased from the landscape, with the notable exception of a few isolated parks (e.g. Mt. Douglas Park and Christmas Hill), as shown in Chapter 4. Disturbances to terrestrial ecosystems include vegetation clearing and soil disturbance associated with development and agriculture, as well as invasive species. However, unlike natural disturbances that were for the most part localised and periodic, allowing time for recovery, the current regime entails a "press" (i.e. sustained) disturbance that makes reorganisation and recovery difficult (Reeves *et al.*, 1996; Bengtsson *et al.*, 2003).

Two alternative stable states in the terrestrial landscape could therefore be defined as vegetated (primarily with native forest/woodland), and barren, characterised by large areas of impervious surfaces, compacted/disturbed soils and trampling, as represented in Figure 6.1. In similar terms, a wet/vegetated vs. dry/barren transition-state model has been described for the Sahara/Sahel region (Scheffer *et al.,* 2005). In that model, a threshold of precipitation leads to widespread vegetation cover, while vegetation in turn contributes to more precipitation; at the site scale, plants provide micro-sites with a favourable water balance and protection from sun and wind (Scheffer *et al.*, 2005). While such relationships between vegetation and rainfall are unknown for Swan Lake watershed, the anthropogenic influences may act in similar ways to maintain either alternative state. For example, the “urban barrens” state can present many challenges to successful restoration, due to changes in runoff regime, loss of organic matter and compaction of soils, poor air and water quality, and the prevalence of invasive species (Suding *et al.*, 2004). Furthermore, areas that are already degraded are often chosen for development (compared to a healthy native ecosystem, which may receive more protection in local land use planning). Thus the legacy of land clearing, combined with ongoing disturbances, maintains a dysfunctional ecological landscape. Since there are so many factors maintaining this (degraded) state, the state could be thought of as resilient and/or resistant: small changes for the better (e.g. small-scale stream restoration) or worse (pulses of nutrients) are not likely to significantly change the behaviour of the system (Walsh *et al.*, 2005), nor to transform it to a different stable state.[3] Figure 6.2 shows a simple model representing feedbacks of these alternative stable states.

The “urban forest” could then be defined as a transitional land cover type that represents an unstable state, where a shift to either side could occur, depending on social mechanisms (e.g. tree-planting incentives) and ecosystem factors such as the

3 Alberti and Marzluff (2004) propose a similar set of alternative states, represented by “natural vegetation” vs. “sprawl,” and suggest an intermediate state of “mixed settled/forested” lands confers more resilience than either state at its fullest, since neither state can maintain both ecosystem and human functions.

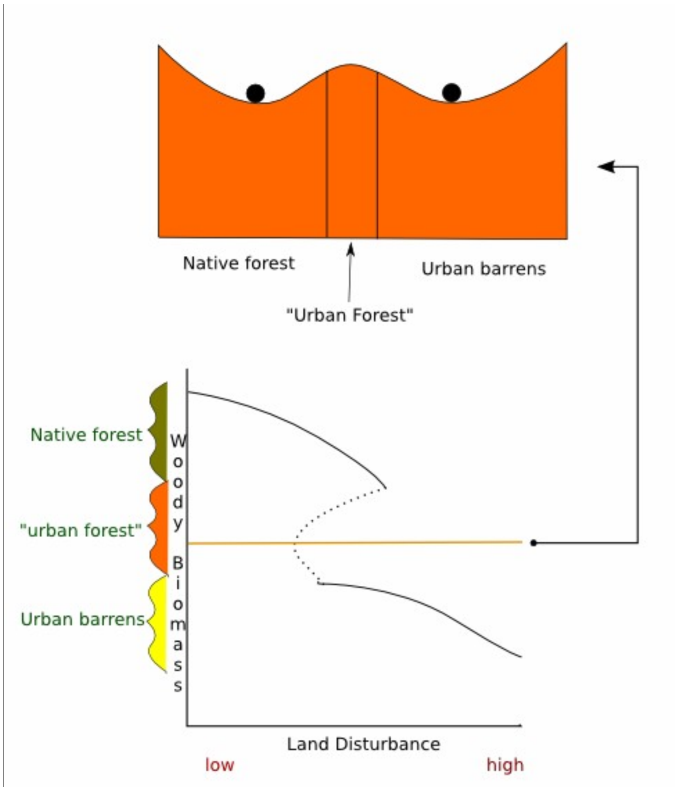

Figure 6.1. Forested vs. urban landscape transition-state diagram (image by the author)

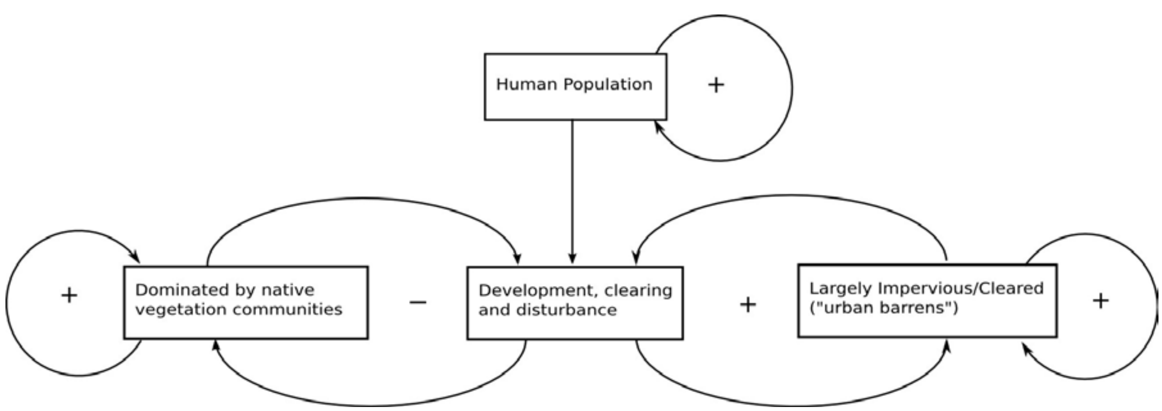

Figure 6.2. Diagrammatic sytstems model* illustrating positive (+) and negative (-) feedback loops that maintain either a native-vegetated or largely cleared state in upland areas of Swan L. watershed, with development and clearing mediating either state

NB: all such systems models were drawn by the author, based on the process outlined in Bennett et al. (2005).

susceptibility of urban trees to disease. The urban forest could also be thought of to include engineered ecosystems such as green roofs, that may fulfill some of the functions of native vegetation, yet fit in a highly urbanized environment. Urban forests perform a number of functions important to watershed health, including sequestering/storing carbon, intercepting rainfall and increasing infiltration (reducing stormwater runoff), removing air pollution, and mitigating the urban heat island effect, thus reducing air conditioning needs (McPherson *et al.*, 1997; Asadian and Weiler, in press; Luymes, 2000). Such ecosystem services are becoming increasingly recognized (UFSI, 2008), yet there are few examples of integrated management or planning of urban forests at the watershed scale. As stated in Table 6.1, the upland ecosystems of Swan Lake watershed are thought to be in the K stage of the adaptive renewal cycle due to limited vegetation cover, an over-connected and relatively homogenous landscape with little patchiness or refugia that could help ecosystems to recover from disturbance (Berkes and Folke, 2002; Schaefer, 2009).

Wetlands and Riparian Areas

Wetlands and riparian areas provide habitat for many species that are important in both terrestrial and aquatic ecosystems; they also help to regulate micro-climate, cycle nutrients and retain and replenish surface and groundwater (Mitsch and Gosselink, 1986). The wetland and riparian communities present in Swan Lake watershed and the general region prior to urban development were diverse and numerous (Chapter 2; Appendix A).

Several wetlands in Swan Lake watershed that have now been drained would have contributed to overall watershed resilience with habitat complexity and diversity, buffering hydrological disturbances, and filtering/processing nutrients to limit downstream eutrophication. The only large wetland area left in the watershed today surrounds Swan Lake. As shown in Chapter 4, the composition and structure of this wetland has been altered and today it is dominated by invasive reed canarygrass with low diversity, representing an alternative state to the woody shrub-dominated state of the past. Furthermore, the shrub community also contains a high proportion of invasive species in the understorey, potentially limiting resilience of the shrubs to disturbance.[4] The grass-dominated state was likely a direct and indirect result of agriculture (see Appendix A), however urbanization helps to maintain this state since reed canarygrass is tolerant of widely fluctuating water tables typical of urban wetlands, and to excessive sediment and nutrient loading (Kercher and Zedler, 2004). Thus the grass-dominated state is itself resilient, as indicated by its long-term persistence over a large area, and some management action may be required to "break down" this resilience and re-establish a native plant community (e.g. Suding *et al.,* 2004). A strategy was implemented to accomplish this goal, with good preliminary success, as summarised in Appendix D. A systems model diagram is shown in Figure 6.3, illustrating some of these feedbacks and interactions. As stated in Table 6.1, the Swan Lake wetlands are thought to be in the r-to-K stage of the adaptive renewal (Panarchy) cycle, since the grass has effectively colonized large areas and appears relatively stable.

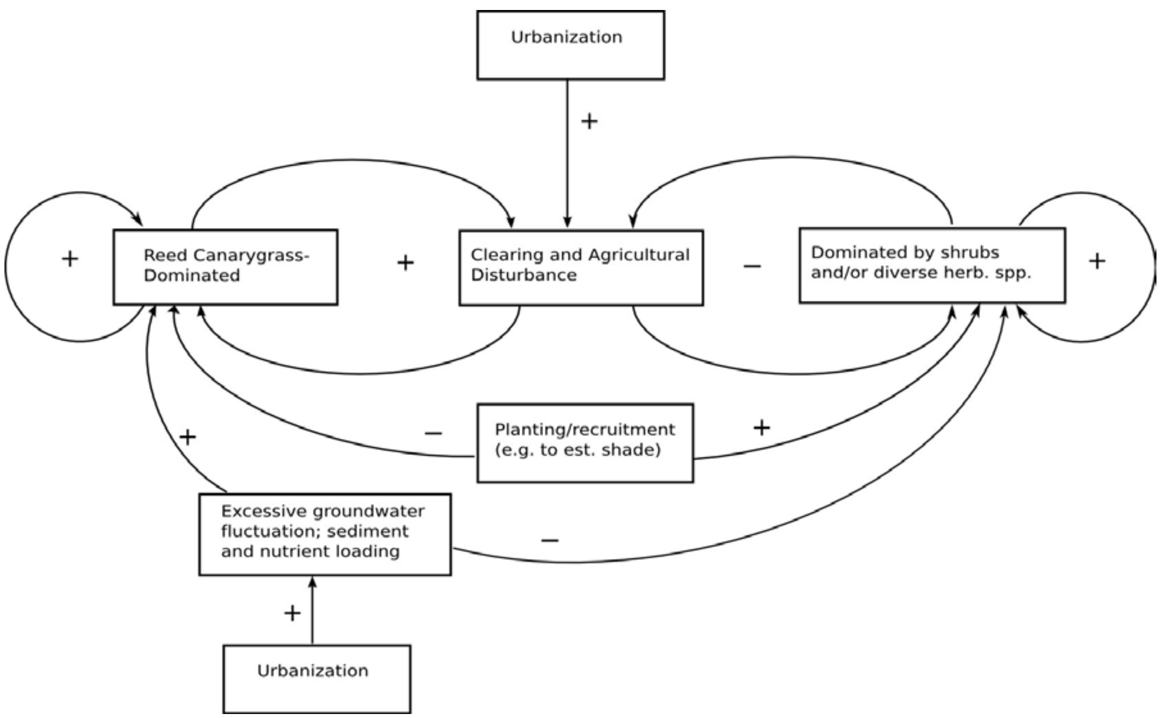

Figure 6.3. Systems model showing multiple factors related to urbanization contributing to present dominance of Swan Lake wetlands by reed canarygrass

4 Diversity is important to resilience insofar as different species provide functional redundancy, where, if a dominant species is lost, a minor species can expand and compensate for the loss of ecological function (Walker *et al*., 1999).

Stream channels

In the past, the streams of the watershed can be assumed to have been for the most part "properly functioning," due to features such as meanders, floodplains and large wood and rock, and dynamic channel adjustments, that dissipated the energy of high flows without substantial erosion.[5] Large numbers of salmon spawned in Colquitz Creek and the lower reaches of Swan Creek and in the past they may have ascended as far as Swan Lake and possibly into the lower reaches of Blenkinsop Creek.

As shown in Chapter 3, most of the stream channel length assessed in this study is degraded, i.e. unable to dissipate energy nor provide water purification, habitat and other functions. This is due to a combination of factors beginning with the initial land clearing in the watershed (Chapter 2), and progressing through decades of stream channel straightening and lowering, removal of riparian vegetation, and increasing impervious surfaces that accelerate erosion and down-cutting. As shown in Chapter 5, Blenkinsop Creek is particularly susceptible to flashy flows that serve to reinforce the degraded state, while Swan Lake and its wetlands attenuate some of this erosive energy. As shown in Figure 6.4, riparian vegetation, soils and channel form serve to dissipate stream flow (hydraulic) energy in healthy streams, yet urbanization combined with high rainfall events can push a system into a degraded state, particularly when vegetation and soils are also degraded. The streams are thought to have low resilience to disturbance, and to be over-connected due to stream channel simplification, thus to be in the K stage of the adaptive renewal cycle.

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5 Although indigenous management undoubtedly had effects on the landscape, there is no indication in the historical literature that widespread soil disturbance or erosion were present when Europeans arrived.

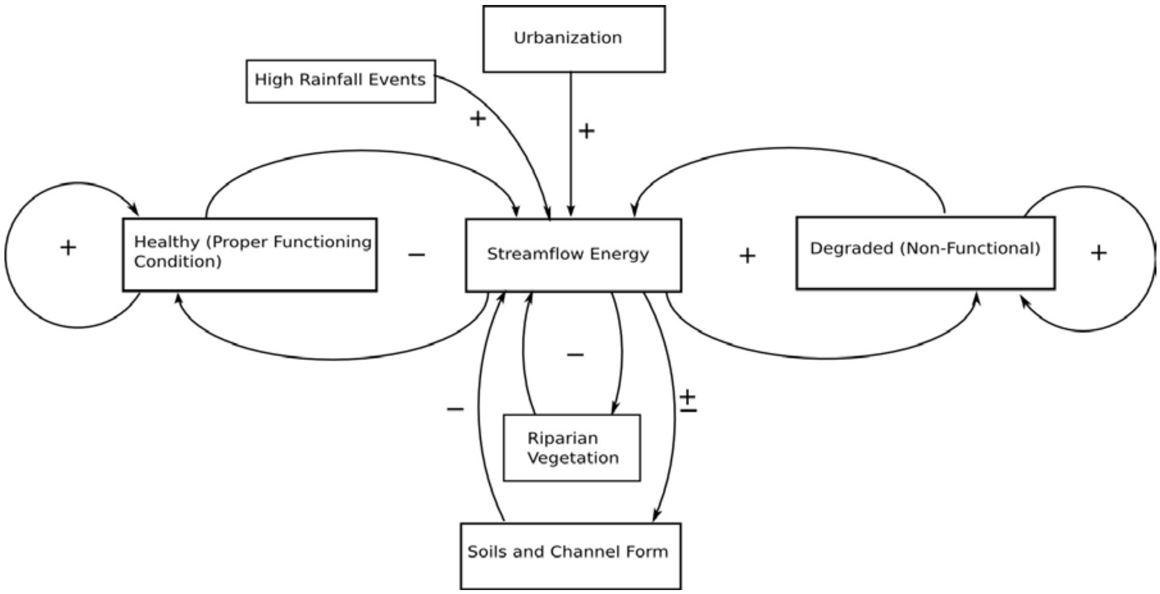

Figure 6.4. Systems model of key processes affecting biophysical stream condition in Swan Lake watershed

Eutrophication and Lakes

Shifts in lake ecosystems, usually from clear water to turbid water, are some of the most well-studied examples of ecological resilience and alternative stable states. The interacting factors contributing to the change from clear-water to turbid[6] can be briefly summarized as follows (paraphrased from: Scheffer, 2004; Carpenter and Cottingham, 1997):

When nutrient loading is low, internal mechanisms such as zooplankton grazing and storage of nutrients in plant biomass of emergent and submersed species, initially help to maintain clear water and high dissolved oxygen. As nutrient loading increases, e.g. due to agricultural runoff and sewage pollution (sport fishers may also contribute to the problem by removing larger piscivorous species), a threshold is then reached when a sudden change occurs, i.e. the resilience of the clear-water state is exceeded. Cyanobacteria and filamentous green algae blooms then become common, leading to: increased turbidity that suppresses submersed vegetation; low dissolved oxygen (due to decomposition);

6 Note however that some lakes are naturally eutrophic, thus the shift does not always occur exactly as described here (Reavie *et al.*, 2000).

transfer of phosphorus to sediments; and fish kills due to anoxic conditions. Furthermore, turbid water conditions allow benthic fishes to proliferate, which help to re-suspend sediment. Bottom-feeding fish also prey on zooplankton, further preventing control of phytoplankton. This state becomes self-maintaining, as anoxic conditions in the lower water levels lead to reducing conditions, under which iron is converted from Fe^{3+} to soluble Fe^{2+}, introducing iron-phosphorus compounds into solution and recycling P.

It is very likely that many of these processes are active in Swan Lake. As described in Chapter 2, the lake was once suitable for swimming and trout were common, thus we can assume generally high oxygen and clear water conditions in the early 20th century and before. Due to a combination of point source organic pollution in the past (Chapter 2) and non-point source nutrient loading that continues today (Chapter 5), seasonal algae blooms and changes to the littoral and wetland plant community show a shift to the turbid water state has occurred. The alternative states described above are represented in Figure 6.5, illustrating that nutrient loading, combined with P recycling from sediments due to low oxygen, help to maintain the turbid state, particularly when grazing (of phytoplankton by zooplankton), and flushing, are limited. As indicated by the large algal biomass visible in thick floating mats in summer, the state is well advanced in the K stage of the adaptive renewal cycle.

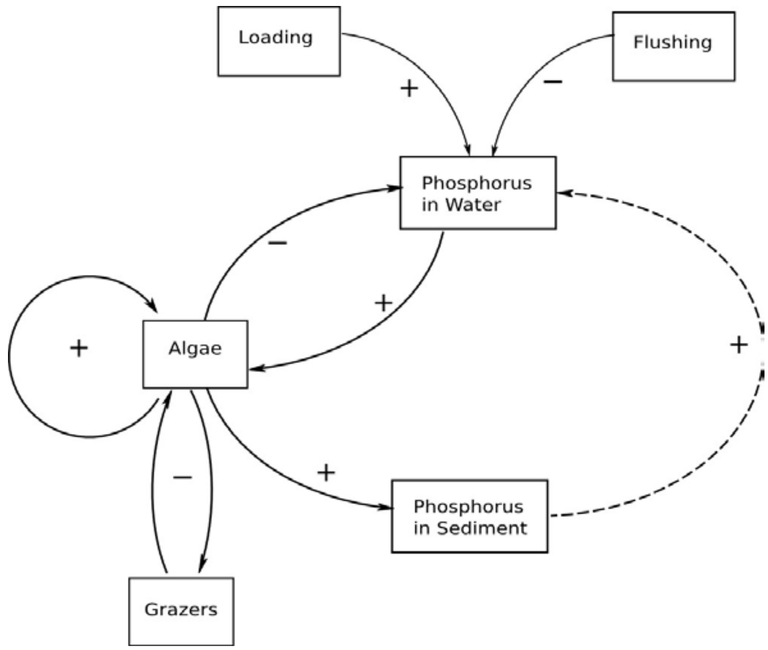

Figure 6.5. Systems model for Swan Lake, showing interactions among phosphorus and algae

6.2. Watershed-Scale Resilience and Indicators

A complex ecosystem consists of a set of nested hierarchies (or, more precisely, panarchies) (Holling, 2001), while an urban watershed entails a "coupled human and natural system" (Liu *et al.*, 2007), meaning that feedbacks between different scales, and between human and natural processes, have important effects. Small/rapid systems contribute information to large/slow systems, and vice versa, contributing to the overall system identity and function (Holling, 2001). For these reasons, a thorough understanding of the system cannot be derived from analysis of any one component in isolation. The system models shown above must therefore be acknowledged to feed back into one another; although an overall watershed systems model is beyond the scope of the present study, a general representation of some of the more obvious interactions, in terms of water and energy flows, is shown in Figure 6.6 (for simplicity, energy imports/exports are not shown). Thus it is apparent that Swan Lake, as perhaps the best-studied ecological component of the watershed, is strongly influenced by outside processes.

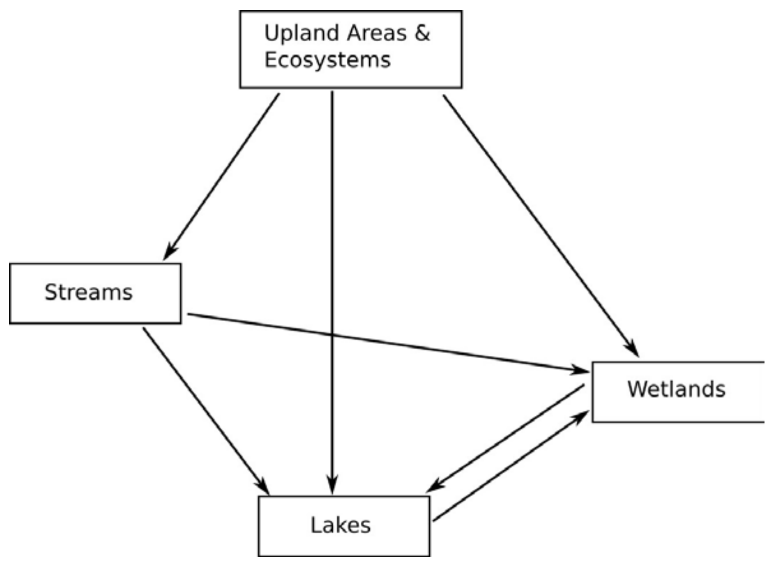

Figure 6.6. General representation of watershed scale interactions (water and nutrients/energy)
(image by the author)

The importance of scale can also be illustrated as in Figure 6.7, where both natural and human components are shown. Solutions to problems in watershed health and resilience must also be devised at this range of scales, as discussed below.

Water quality is one factor influenced by a number of cross-scale processes in the watershed. Water quality is poor in Blenkinsop Creek, Swan Creek, and in Swan Lake, as discussed in Chapter 6. This precludes sensitive species such as salmonids, and may have toxic effects on a variety of organisms. Although point-source pollution flowing into Swan Lake was reduced after sewage and industrial effluent were diverted in the 1970s (Chapter 2), non-point source pollution continues largely unabated today. Furthermore, there is currently no program of water quality monitoring undertaken by any organisation for this watershed, making it impossible to pinpoint hot-spots or to direct management recommendations toward the areas of the watershed in most need of mitigation.[7]

7 The Capital Regional District does have a stormwater monitoring program, but monitoring sites are primarily located at marine discharge points and do not currently include any locations within Colquitz or Swan Creek/Swan Lake watershed (Capital Regional District, 2007).

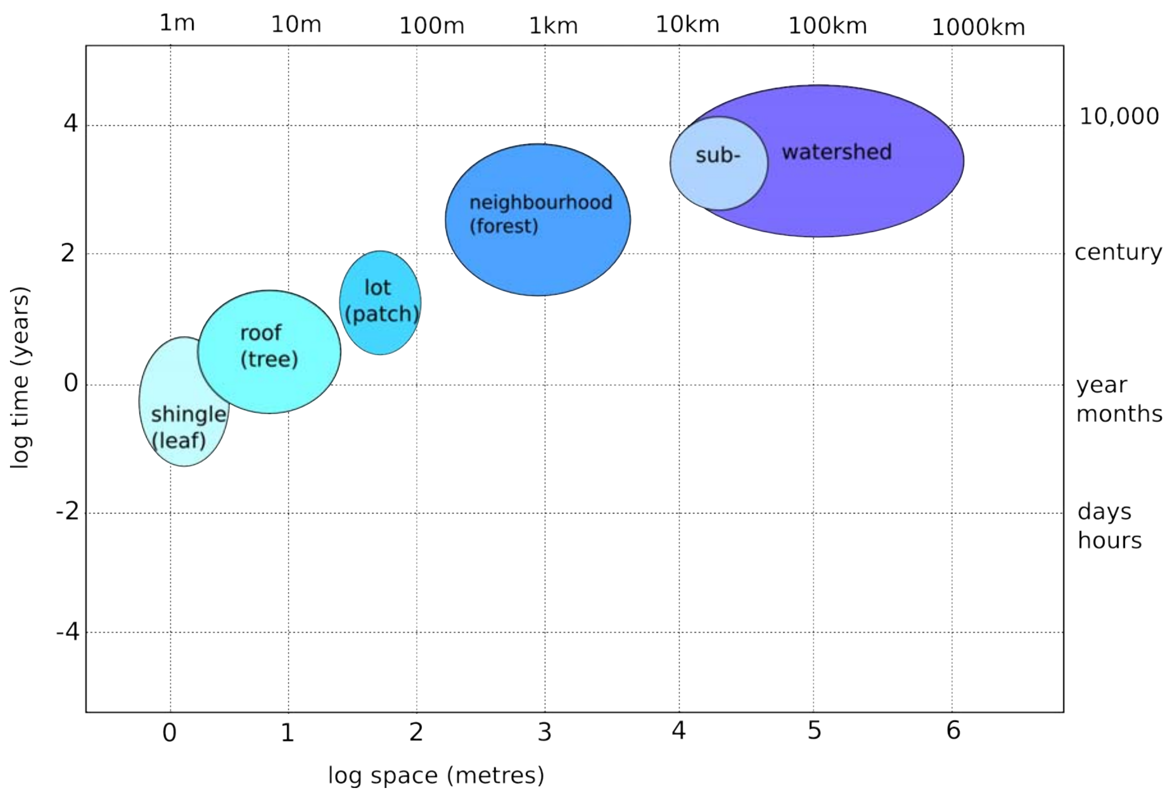

Figure 6.7. Representation of an urban watershed as a nested hierarchy, with natural structures shown in parentheses (modified from Holling, 2001)

In order to assess resilience via interactions between ecosystem processes and across scales, Ludwig and Smith (2005) recommend a four-step process. Although the scope of this study did not allow for stakeholder consultation as recommended by these authors, Figure 6.8 represents a preliminary attempt to characterise the problem in these terms as a basis for discussion. The example focuses primarily on the resilience of water quality to land use. Figure 6.8 is therefore based on the following assumptions about the landscape:

- Local site management may have a large direct effect on the local landscape. For example, new development is normally undertaken via extensive clearing, grading and vegetation removal. Building configuration (e.g. footprint of impervious area) determines the volume of surface runoff from small areas, contributing to larger-scale hydrology. Agricultural practices in the watershed normally involve annual cultivation and soil disturbance. Erosion and sedimentation then affect local, (and, cumulatively, regional) water quality (e.g. eutrophication in Swan Lake, as discussed in Chapter 5). Urban site management may include construction practices, spill response and landscaping practices (e.g. fertilizer and pesticides), as well as residential property management at the single lot scale.

- At the organisation/property or neighbourhood level, policies and plans in turn drive practices on the ground. For example, erosion and sediment control plans and best management practices may help to prevent site runoff, while site and infrastructure design (e.g. building design, subdivision layout, impervious area, storm drains or low impact development) determine to a large degree the runoff characteristics at the lot scale. On farms, the choice of crops, and buffers (or lack thereof) will affect site conditions. Community groups can play a role in helping to restore degraded areas, and providing recognition of agricultural stewardship at this scale.[8]
- At the municipal scale, municipal managers and regulators influence urban development through zoning, permitting and community planning. Local markets and business viability of local farms provides the economic capacity to adopt improved practices, which may affect crop yield and/or ecological processes. However, competition with cheap imported produce limits the influence of consumer demand on (and willingness to pay for) locally grown products (R. Galey, pers. comm.). Also, there is usually a lack of feedback from effects on ecosystems to farm practices.
- At the provincial/federal level, there are several regulations that relate to water quality and habitat, including the federal Fisheries Act, the provincial Water Act and the provincial Riparian Areas Regulation.[9] There may also be policies

8 For example Galey Farms in the Blenkinsop Valley was recognised as a “conservation partner” by The Land Conservancy (2005) for supporting riparian restoration and reducing pesticide use, also helping their corporate image (Barraclough and Hegg, In Press).

9 These in fact apply to property developers directly, but for simplicity they are shown influencing municipal management in the diagram.

relevant to municipal operations, but these are not usually as prescriptive as regulations.

Some of the interactions between these actors and practices and ecosystems are shown in In Figure 6.8, the weight of the line represents the relative strength of the interactions between actors, ecosystems and processes. This diagram shows that several possible feedbacks are weak or lacking. For example, there is currently no provincial, regional or municipal water quality or biodiversity monitoring carried out in the watershed. Monitoring has the potential to help inform policies regarding development and agriculture and to create an adaptive management loop to inform policies and measure their effectiveness, creating institutional flexibility to respond to crises (e.g. Berkes and Folke, 2002). Also, economic incentives are lacking, that could encourage farmers to preserve ecological integrity, for example to restore unproductive land to native ecosystems, establish buffers along streams or carry out riparian restoration. The Municipality of Saanich enforces a bylaw requiring on-site stormwater management for commercial developments, helping to limit runoff (District of Saanich, no date), however this regulation is not tied to specific performance criteria as it is in some other jurisdictions (e.g. Washington Dept. of Ecology, no date). In addition, incentives are lacking for implementing or preserving 'green infrastructure' such as native trees and natural areas, constructed wetlands, green roofs, etc., which could substantially improve water quality and other ecological objectives. In conclusion, there are several "mis-matches" in cross-scale interactions that serve to degrade the resilience of water quality to land use effects.

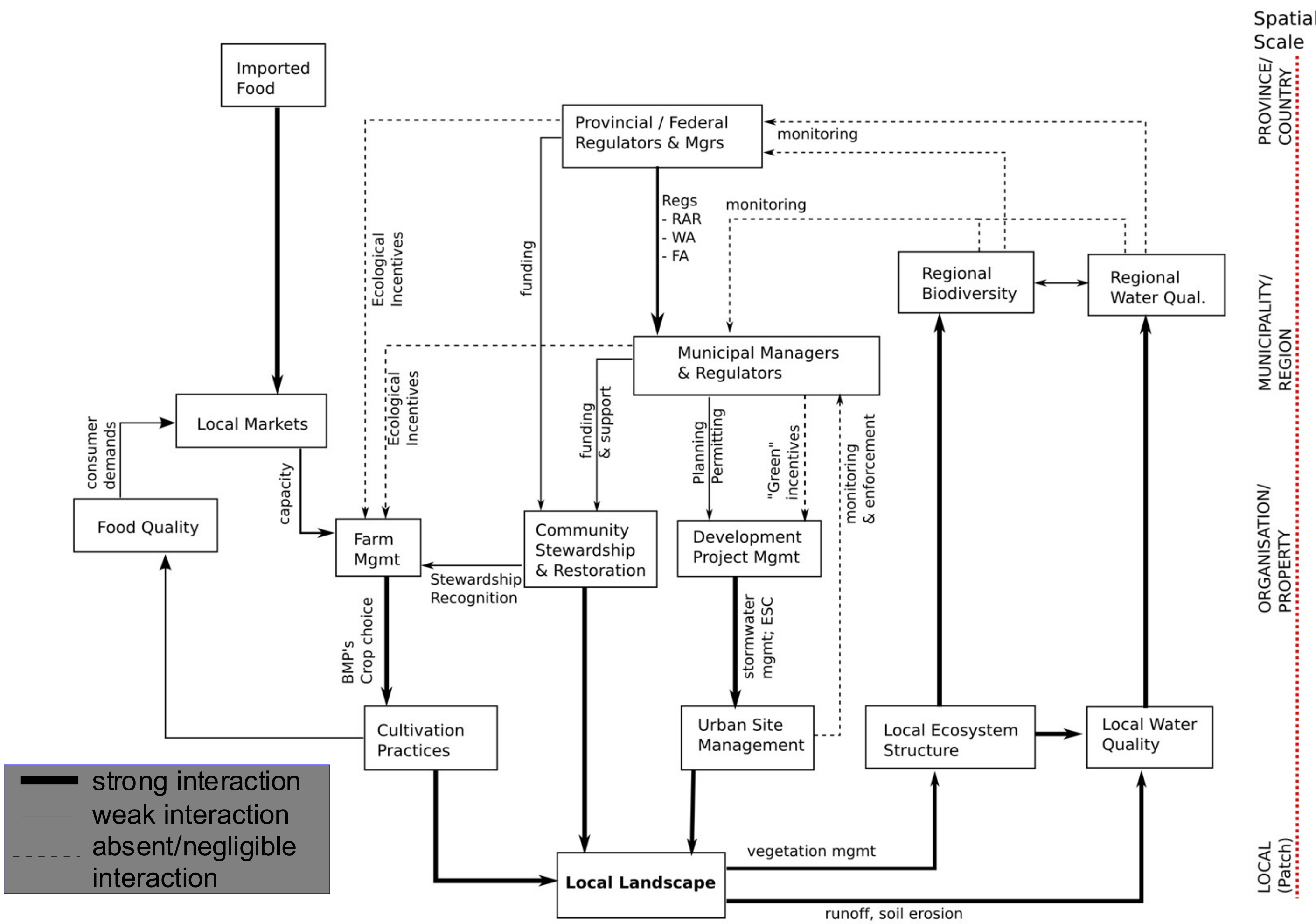

Figure 6.8. Model of ross-scale interactions in Swan Lake watershed (modified from Ludwig and Smith, 2005)

"Ecosystem Ageing"

Another way of considering water quality at the landscape scale has been called "ecosystem ageing" (Ripl, 2003). This refers to the accelerated loss of mineral elements from the landscape due to human disturbance, and has been used as a metric of watershed function (Procházka *et al.*, 2001). Human land use tends to increase sediment runoff by orders of magnitude above natural levels, as clearly shown in long-term sediment records in marine bays (Ripl and Hildmann, 2000). These essential elements originate from soils in the watershed, and are mobilised when soil is exposed and eroded, "irreversibly" depleting soil fertility and hence productivity, as well as potential ecosystem services from the landscape (Palm *et al.*, 2007; Ripl, 2003). Erosion contributes not just minerals but also phosphorus that is bound to soil, exacerbating eutrophication and requiring farmers to apply more fertilisers to compensate for lost nutrients, creating a vicious cycle that is a worldwide concern (Harris, 2003). As shown in Chapter 5, there are very high levels of cations (Ca^{2+}, Na^{+}, K^{+}), both in the inflow water to Swan Lake, in the lake itself, as well as in the sediments. Minerals that are flushed through Swan Lake flow into Portage Inlet, where sediment deposition has been noted as a problem for many years, potentially affecting marine life through increased turbidity, smothering and nutrient loading (Capital Regional District, no date).

Mineral loss is an indicator of a "leaky" system in terms of energy and matter, in contrast to a more "mature" system that has tighter networks and reduced energy gradients and matter loss, as discussed in Chapter 1 (Ulanowicz, 1986; Schneider and Kay, 1994). This is particularly relevant to human-dominated landscapes such as urban watersheds, where matter losses occur over prolonged periods of time. Therefore ecosystem ageing may help to clarify the rather elusive concept of "ecological health," as discussed in Chapter 1. By this measure then (the loss of minerals and nutrients from the land), Swan Lake watershed appears to be "prematurely ageing," suggesting impaired health.

"Green water" flows and solar energy dissipation

Water vapour flows are related to matter losses, since disturbed and cleared landscapes typically exhibit high matter losses as well as increased surface temperature and lower evapotranspiration (Procházka *et al.*, 2001). The continental portion of the hydrological cycle has recently been portrayed as a combination of "blue water," i.e. liquid fresh water in the form of ice, rivers and lakes, and "green water," i.e. the portion of the water cycle directed by plants through interception/evaporation of precipitation, and transpiration of soil water through leaf pores, with the latter forming approximately 65% of this water budget (Rockström and Gordon, 2001).

This type of analysis is useful for characterising the effects of land cover change. For example, in Australia, large-scale deforestation and land conversion to crops and grazing has reduced water vapour production by about 340 km^3 per year across the continent, leading to higher groundwater tables and widespread soil salinization (Gordon *et al.*, 2003). At the watershed scale, the "green water cycle" is important for redistributing solar energy in the landscape (via evapotranspiration), as well as for maintaining the ecosystem services provided by vegetation (Pokorný, 2001; Scheffer *et al.*, 2005). In the urban environment, steep temperature gradients are typically created, for example between highly radiative paved areas and cooler vegetated residential or rural areas. These gradients lead to convection, air turbulence, increased sensible heat and urban heat island effect, potentially affecting larger scale climate processes (Pielke and Niyogi, 2008). On the other hand, vegetation helps to buffer these gradients, moderating temperature extremes and creating more hospitable conditions for residents, largely through evapotranspiration and the partitioning of solar radiation to latent heat (Dow and DeWalle, 2000).[10]

Pokorný (2001) estimated 70 to 80% of solar radiation in a temperate region is transformed to latent heat in a water-saturated and vegetated landscape, and 5-10% to sensible heat; by comparison, in a drained field or urban parking lot only 5-10% is partitioned to latent heat and 60-70% to sensible heat (soil heat flux and reflection were

10 When water is available in the landscape, solar radiation is used in the process of the phase change from liquid water to water vapour, instead of causing an increase in air temperature; this latent heat is in turn released when water vapour contacts a cooler surface and condenses, helping to redistribute energy and mitigate the urban heat island effect.

estimated to be the same in both scenarios). Following this rationale, I used local (Vancouver BC) values for solar radiation, averaged by day over the growing season, and varying latent heat functions over different landscapes, to calculate the value of the "lost service" of energy dissipation in Swan Lake watershed due to vegetation clearing and wetland drainage (Townsend and Hegg, In Progress). This value was estimated at 4.5 billion MJ over a single growing season (May to September), with an energy value equivalent to 180,000 tonnes of coal per year; at $81/tonne[11], this can be expressed as a theoretical market value of $14.6 million (Townsend and Hegg, In Progress). Although this value is not directly transferable to the energy cost of cooling, it helps to illustrate the magnitude of the effects of land use change on the energy balance. With some more detailed analysis and modelling, this type of study could be used to link urban heat island with ecosystem restoration and incorporation of "green infrastructure" such as green roofs, bioretention areas and trees as a climate adaptation strategy (e.g. Mitchell *et al.,* 2008), in addition to the carbon sequestration service performed by woody vegetation and healthy soil. Furthermore, due to its importance for solar energy dissipation, I suggest that vegetation cover (extent, type and condition compared to the pre-development landscape) represents a possible metric of landscape-scale resilience.

Stream networks, connectedness and flow patterns

Studies that address ecological resilience often tend to focus on the consequences of excessive stability, for example in the "command and control" paradigm of maximum sustainable yield and forest fire suppression (Holling and Meffe, 1996). In hydrology, excessive stability is apparent in rivers subject to highly stabilised flows due to dams, leading to reduced biodiversity (e.g. Palmer *et al.*, 2005). However, increased variability ("flashiness") as described for Swan Lake watershed in Chapter 5, also leads to a decreased ability to absorb disturbances and maintain the defining structure and function of a healthy stream. Excessive and frequent erosive flows, a nearly ubiquitous phenomenon in urban areas, tend to erode stream banks, scour and damage benthic

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11 This value is the May, 2009 spot price for coal according to the Energy Information Administration (http://www.eia.doe.gov/)

habitat, and lower groundwater tables (Walsh *et al.*, 2005). As described below, these processes are also closely linked with water quality and biochemical cycling. One challenge with characterising flashiness in this study was a lack of an undeveloped watershed with similar topographical and meteorological conditions to use as a reference, since few streams in the region are gauged (Water Survey of Canada, pers. comm.). Therefore, dimensionless metrics applicable to flow data would be useful in order to compare this system with other gauged streams. In this study, such an analysis was not possible, due to the short time scale of the study, as a number of years of flow data are usually required for meaningful analysis. However, there are several indices of flashiness[12] that could be applied to this and similar watersheds as surrogate measure of resilience, once sufficient data has been collected.

One indicator, called the the coefficient of variation of hourly flow (CVHF) (McMahon *et al.*, 2003), may be particularly well suited to estimating resilience. CVHF is the ratio of variability (e.g. standard deviation) of streamflow (or stage) to the mean annual discharge or stage. Flashiness metrics are also calculated in this method, i.e. the rate of increase or decrease in stage or discharge, and the duration of extreme river stage (McMahon *et al.,* 2003). Increased variance has been shown to precede a regime shift between alternative stable states in a variety of ecosystems, and has been proposed as an "early warning signal" of potential use to resource management (Carpenter and Brock, 2006). Litzow *et al.* (2008) pursued this principle in a study of marine benthic fisheries, and speculated that the collapse of the North Pacific cod fishery might have been avoided if the increased variance preceding the collapse had been recognised. In urban watersheds, degraded conditions can occur even in watersheds with a relatively low impervious area (e.g. well below 10% imperviousness previously thought to represent a threshold) (Booth *et al.*, 2004). Therefore models that incorporate variance in streamflow and flashiness

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12 For example: TQ_{mean} , the fraction of the year that the daily mean discharge exceeds the mean annual discharge (Booth et al., 2004; Konrad et al., 2005); $T_{0.5}$, the fraction of time over multiple years that discharge exceeds the flood discharge that occurs on average twice a year (Booth et al., 2004); the coefficient of variation of annual maximum streamflow (CVAMF) (Konrad *et al.*, 2004); the coefficient of variation of hourly flow (CVHF) (McMahon *et al.,* 2003).

indices, combined with estimates of ecological function (e.g. IBI and/or PFC), may provide a means to characterise alternative stable states in stream conditions as well as the resilience of the streams to anthropogenic disturbance. A basic requirement of this type of study would be long time-series flow data for urban streams.

Network connectivity is yet another potential measure of resilience. Urbanisation tends to increase drainage density, with artificial channels such as agricultural and roadside ditches and storm drainage networks, resulting in increased internal links that amplify the energy of flood events and pollution from point and non-point sources (Paul and Meyer, 2001). In terms of system theory, over-connectedness can result in decreased resilience by making the overall system more vulnerable to disturbances (Janssen *et al.* 2006; Holling, 1986). Swan Lake watershed is thus over-connected by a system of stormwater pipes (Figure 6.9), whereas in a forested watershed, or an urban watershed designed to mimic a forested landscape, small perturbations are limited in the scale of their influence. Other studies have demonstrated a positive correlation between high landscape connectivity and degraded stream conditions, where connectivity is defined as road network density or flow path to a stream channel (e.g. McBride and Booth, 2005; Alberti, 2005). However, few studies appear to have addressed connectivity of the storm drain network itself. GIS tools and information theory could therefore be used to quantify landscape connectivity, and to measure effects of various watershed planning approaches. In terms of managing for increased watershed resilience, the objective would be to reduce connectivity of the drainage network (at least for the majority of flow events) by gradually taking portions of the catchment “off-line,” beginning in the headwater areas, through the use of “green infrastructure” and “low impact development” techniques. As stated in Table 6.1 and the systems models shown above, the various assessed components of Swan Lake watershed (lakes, streams, wetlands and uplands) are all in 'undesired' stable states, and are estimated to be in or near the "K" phase of the adaptive renewal cycle, where resilience is lowest (Gunderson and Holling, 2002)[13].

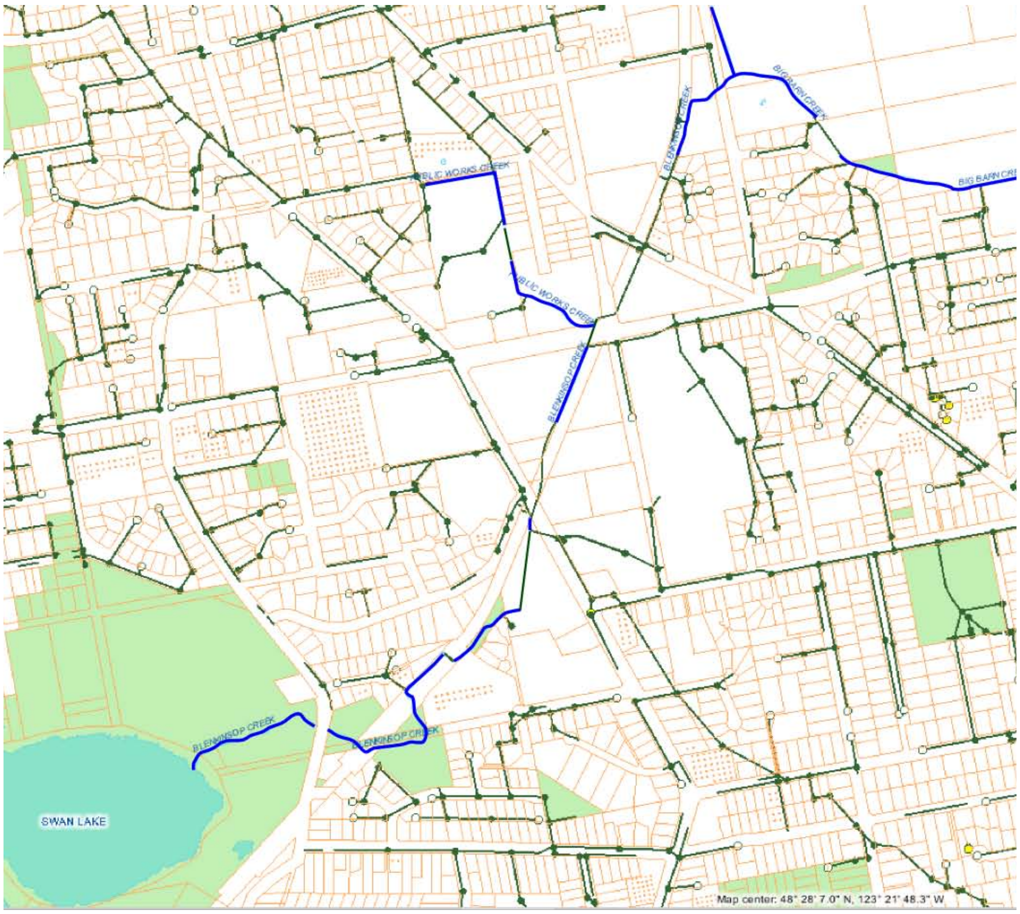

Figure 6.9. Portion of Swan Lake watershed, showing municipal stormwater network (green lines; does not include storm drains on private property); source, Saanich public GIS viewer

The potential resilience indicators at the watershed scale also suggest low resilience. It follows that a crisis will eventually precipitate a "release" and "reorganisation" phase. It remains to be seen how such a crisis (whether anticipated/initiated or unanticipated) may affect social and ecological processes. Some of the factors identified by Berkes and Folke

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13 There is some uncertainty in this assessment of the stages of the cycle; e.g. although stream channels are highly connected and channelized, suggesting the K stage, ongoing erosion and "leakiness" is sometimes associated with the Ω phase, yet has presumably been ongoing for decades, whereas the Ω is normally very rapid (Holling and Gunderson, 2002); these inconsistencies may mean the watershed does not neatly fit the Panarchy model, and/or that additional analysis is needed.

(2002) in successful adaptation to crises include social and ecological memory (e.g. seed banks, habitat refugia, multi-generational knowledge), landscape patchiness (areas in various successional stages) and institutional flexibility, elements that are not immediately apparent in this watershed.

6.3. Summary of Ecological Health and Resilience in Swan Lake Watershed, and Proposed Assessment Tool

Swan Lake watershed, like most urban watersheds, is a complex system that eludes simple metrics of ecological resilience. As discussed in Chapter 1, there are problems with terminology surrounding the concept of ecological health. Resilience theory provides a paradigm with which to evaluate the behaviour of complex systems, that incorporates recent advances in ecological theory. However, it is important to acknowledge that resilience in and of itself is not necessarily the ultimate objective, since undesired states can also be resilient, and since the adaptive renewal cycle includes differing levels of resilience throughout (Holling and Gunderson, 2002). Proper Functioning Condition methodology (Chapter 3), provides a specific definition of ecological function for streams, *i.e.* dissipating energy, filtering sediment, retaining flood-waters, developing channel complexity and supporting biodiversity (paraphrased from Prichard, 1998). Similarly, ecosystems have been characterised as "dissipative ecological units" that function to degrade solar energy and smooth energy gradients, where ecosystem development is seen as a process to "maximize" these functions (Ulanowicz, 1986; Schneider and Kay, 1994). Such concepts do not directly address the role of disturbance, however adding a layer based on Holling's adaptive renewal cycle may still accord with these concepts, since ecosystems have been observed to ultimately depend on the periodic release of bound energy in order to continue to dissipate energy in the long run. I therefore propose a definition of 'ecological health' that may add clarity to ecological assessments:

Ecological health is defined as *the development of ecosystem structures, functions and composition that serve to dissipate energy gradients*[1]*, within a cycle of adaptive renewal*[2] *consistent with the historic range of variability[3], where resilience[4] is maintained around a desired stable state.*

Definition References:
1. as per Odum, 1969; Schneider and Kay, 1994; Ripl, 2003
2. Holling, 1992; Gunderson and Holling, 2002
3. E.g. Landres et al., 1999
4. Holling, 1973; Resilience Alliance, 2007; Folke et al., 2004

The “desired” state implies that human values are necessary to determine the 'health' of the system (*c.f.* Meyer, 1997). This is necessary since various alternative stable states may be possible that are 'healthy' in the sense of maintaining processes that benefit certain organisms (e.g. phytoplankton in a culturally eutrophic lake benefit, whereas people would more likely regard it as unhealthy). The term 'historic range of variability' is used in order to avoid arbitrary justification of a particular management regime that is not based on the landscape history and processes of a site, and to enable management that addresses the dynamic nature of ecosystems (Landres *et al.,* 1999; Egan and Howell, 2001). “Historic” is intended as a broad term that may or may not include previous human management, depending on the site. For example, in the case of Swan Lake watershed, indigenous management should be considered in a “reference” study, since the landscape co-evolved with people and this interaction is thought to have supported ecosystem processes in general (Chapter 2). However, if human management had reduced energy dissipation by the landscape (e.g. large-scale land clearing or soil erosion), it might not be considered as a useful reference. Conversely, if human populations were so small and/or transitory as to have a negligible effect on ecosystem function they might not be considered to have been an important influence.

As mentioned briefly in Chapter 1, eastern theories of nature and energy constitute an approach to health that can be applied to ecosystems. For example, one of the tenets of Chinese Taoist philosophy is known as Five Processes Theory[14] or *Wuxing,* a system that was first codified ca. 350 to 270 B.C.E. (Kaptchuk, 1983). The relationships between the

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14 This system is sometimes called the “five elements” theory, however they are dynamic processes and interrelationships, therefore “processes” or “phases” is the more correct translation (Kaptchuk, 1983).

Five Processes (*water, wood, fire, earth* and *metal*), are based on observations of nature, and the system is most commonly applied to medicine, with each phase corresponding to an organ network in the body, where interactions among processes help to maintain health (Maciocia, 1997).

There are few references to Five Processes in the ecological literature (but see Whang and Lee, 2006, and Wang and Yan, 1998), therefore some of the ecological applications of the theory are proposed here for further interdisciplinary research.

Notwithstanding the complexity of ecological systems, some researchers suggest that critical processes can often be explained with a small number of variables or indicators (Yorque *et al.*, 2002; Walker *et al.*, 2006). Around five variables (the "rule of hand") may represent a suitable number since more than this masks important emergent traits, and fewer is not sufficiently detailed (Holling, 2001).

Diagnostic tools and indices of ecological health, although they necessarily involve simplification of complex ecosystem processes, are useful for providing practical information to managers and the public (Andreason *et al.*, 2001). As stated in Chapter 1, there is currently no widely used system to assess health or integrity of a terrestrial landscape or watershed. The proposed system is therefore based on the following rationale.

1. The proposed five-processes assessment would have similarities to *Proper Functioning Condition* methodology (PFC-M) (Prichard, 1998), inasmuch as it entails a suite of indicators that can be customised to the characteristics of the landscape in question, it is intended to be carried out by an interdisciplinary team, and it may involve either a rapid field assessment or a more in-depth research project. Three categories of attributes similar to those used in PFC are retained: water, soils and vegetation. Although streams are considered good indicators for watershed processes, for comprehensive integration of ecological processes across a watershed, and social influences in an urban setting, additional criteria should be incorporated.

2. The additional categories proposed are “nutrients/elements” and “energy.” These categories are among those used in assessing rangeland health (NRC, 1994), along with water and soils.

3. Nutrient cycles are emphasized by Zalewski (2002) as a fundamental watershed-scale process, along with temperature and light (which I consider within the category of 'energy') and “water mass dynamics.”

4. Energy principles are based on disturbance dynamics, resilience and non-equilibrium thermodynamics. For example, Müller (2005) recommends energy as a category, along with water and matter cycles, while Ho and Ulanowicz (2005) propose several energy-related criteria of “sustainability or health.”[15]

The proposed system is therefore not entirely new, rather a unique combination of previously applied or proposed categories. The combination of western scientific references, with an eastern system of practice with many centuries of applications supporting it, may provide a more robust system than either approach alone. These five processes are represented in a conceptual model[16] in Figure 6.10 and are described in more detail in Appendix G as they relate to Swan Lake watershed. In this diagram, energy from the sun is dissipated by a number of cyclical processes, resulting in limited matter and energy loss (e.g. Ripl, 2003). Positive feedback helps to maintain the resilience of the desired state. In Figure 6.11, human-caused disturbances such as excessive land clearing, soil exposure, and added energy inputs (e.g. fertilisers and increased surface runoff) serve to open the previously 'closed' cycles, mobilising nutrients and matter off the landscape and resulting in reduced ecosystem services (e.g. carbon sequestration, climate cooling).

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15 These criteria involve “maximizing non-dissipative cyclic flows [which] will increase the following: energy storage capacity, which translates into carrying capacity or biomass; the number of cycles in the system; the efficiency of energy use; space-time differentiation, which translates into biodiversity; balanced flows of resources and energy; reciprocal coupling of processes” (Ho and Ulanowicz, 2005).

16 Consumers are also included in the diagram in order to more accurately represent energy fluxes, however this component is not a major focus of the framework, for simplicity.

This representation is not all-inclusive (there are other mutual effects between practically every process), rather it attempts to illustrate some of the more critical interactions. Some examples of potential interactions among all five processes are provided in Appendix G, including explanations based on traditional Chinese theory. A preliminary list of criteria to assess these processes is given in Table 6.2. This is a proposed system that would require further research and collaboration with specialists in various disciplines. The proposed ecological criteria may also need to be tailored to the specific landscape being assessed, and were designed to be general enough to apply to landscapes in different climates and at different scales. The intention is for these criteria to be used by an interdisciplinary team, to assess conditions of an urban or semi-urban landscape. Some possible assessment methods are listed in the table, but additional methods may be necessary. They would likely include a combination of remote sensing, mapping, surveys and field assessments.

Social and economic criteria should also be developed (but were beyond the scope of this study). For example, the presence of watershed stewardship groups and educational programs could indicate awareness and public involvement. Economic criteria could include ecosystem valuation studies to highlight existing and potential values of natural areas and green space, and local economic indicators to evaluate the potential feedbacks to landscape practices as discussed above (Figure 6.8). The criteria could be applied to an entire watershed, and/or to sub-catchments or other smaller areas within a watershed. In Appendix G, Swan Lake watershed is rated against these criteria in a preliminary evaluation (this is an example only, since an interdisciplinary team would be required for a full evaluation). Most questions were answered with “No” or “Unknown,” with the exception of two possible (qualified) “Yes” answers (criteria # 5 and 6). The assessment would be better informed with additional studies in the areas of micrometeorology, urban forest health and soil health, and with long-term monitoring (e.g. hydrology). Nevertheless, by these criteria, the health of Swan Lake watershed is poor, and resilience, of the healthy state to watershed scale disturbances, is low.

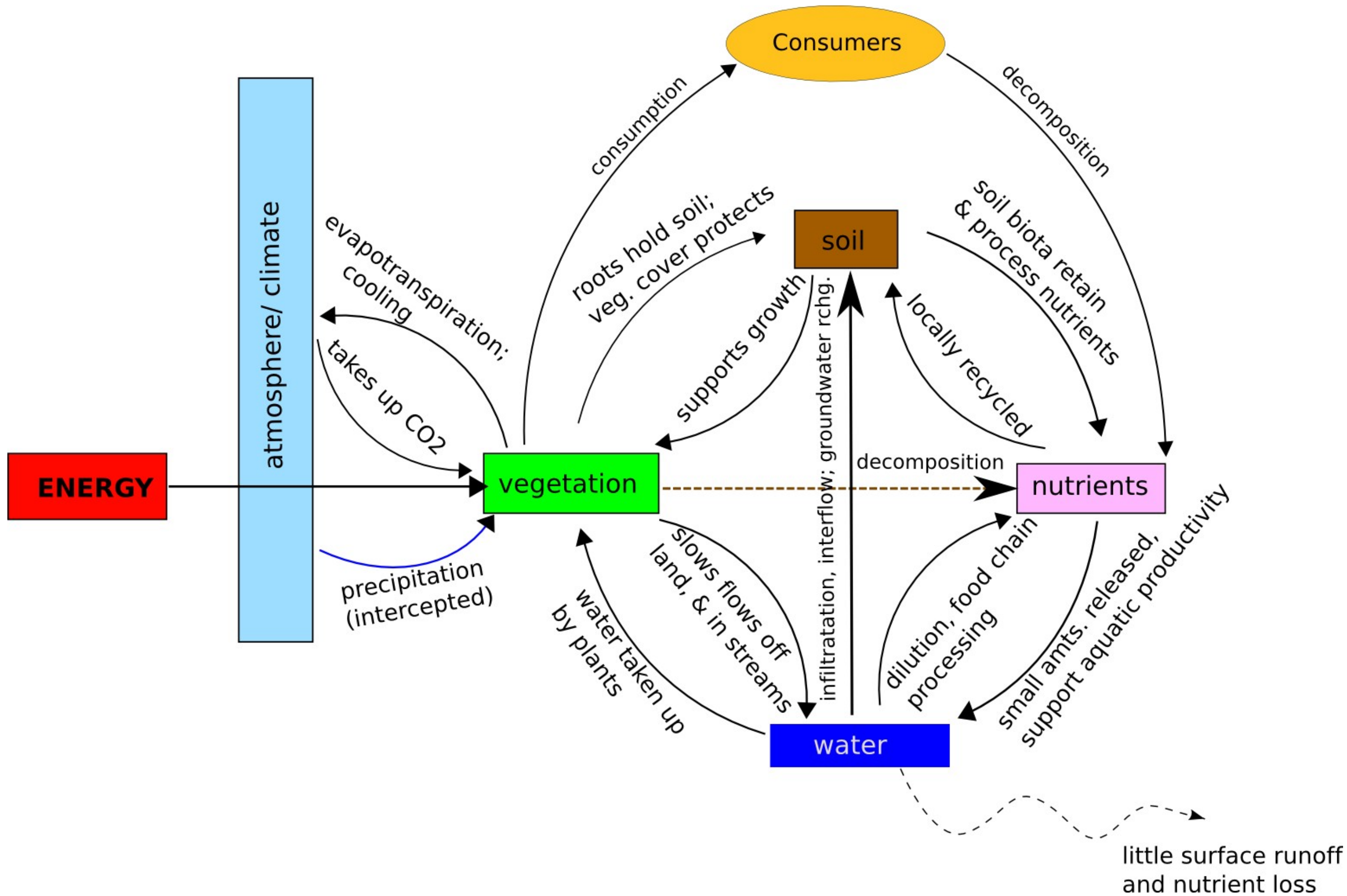

Figure 6.10. Conceptual model: processes in a 'healthy' watershed
(image by the author)

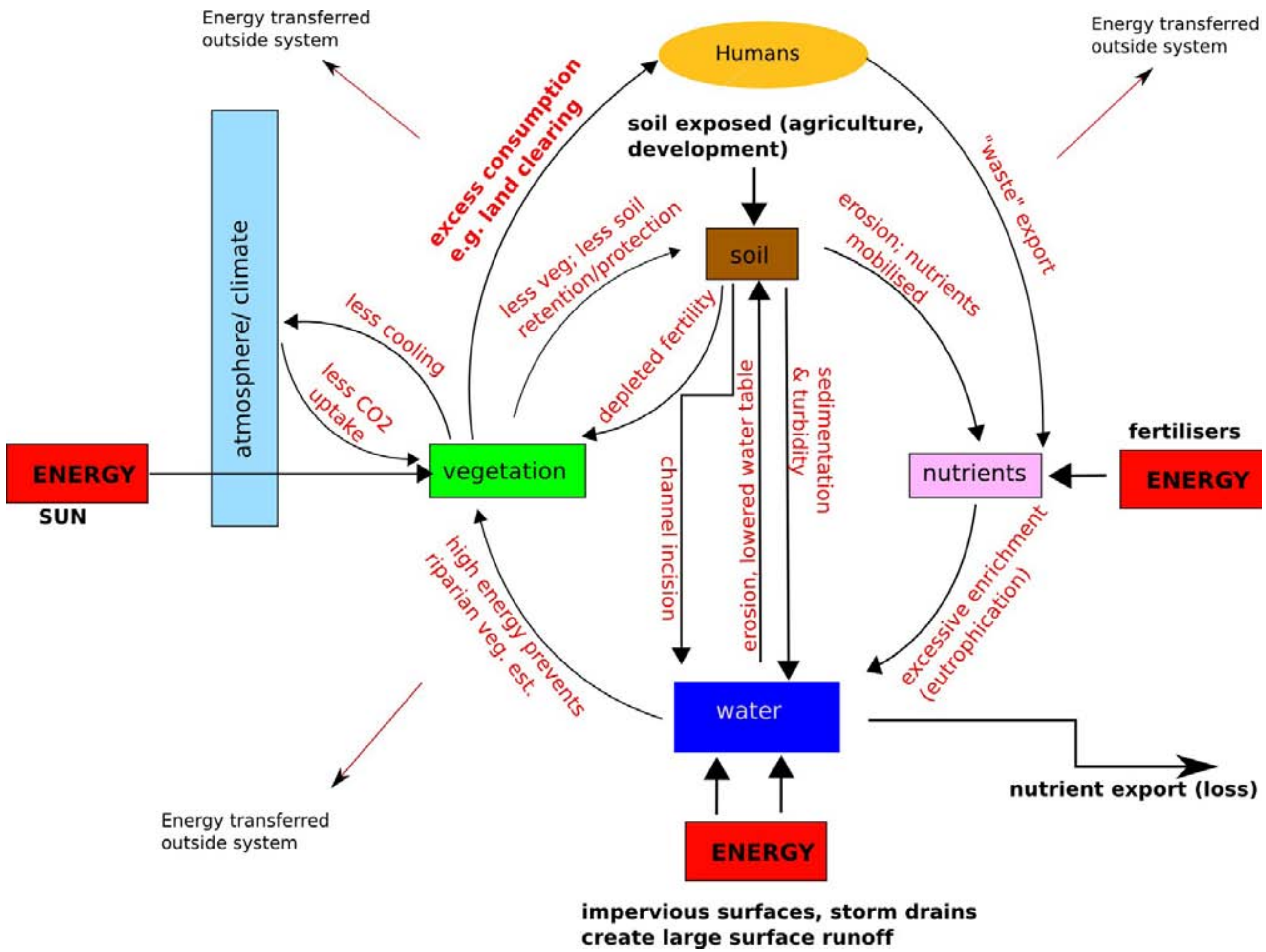

Figure 6.11. Conceptual model: processes in an 'unhealthy' watershed (image by the author)

Table 6.2. Preliminary landscape (watershed) health assessment criteria based on five processes

Cate-gory	Criteria	Possible Measurement Method(s)	Indications of health	Ref
Water	1. Water is supplied to site or across landscape in amounts and frequency from natural sources to support healthy vegetation appropriate to the site.	Vegetation health and composition; soil moisture regime	vegetation consists of appropriate upland/riparian vegetation according to expected distribution for the given biogeoclimatic zone	1
	2. Riparian/wetland areas are healthy and not subject to degradation from upland watershed.	PFC assessment of riparian/wetland areas; monitoring; index of biological integrity (IBI)	Properly functioning riparian/wetland areas (if applicable); no signs of excessive erosion/deposition; presence of pollution-intolerant species	2, 6
	3. Water is intercepted, infiltrated, retained and released (ET) by vegetation in a budget similar to pre-development conditions.	Historical research; Water Balance Model; other hydrol. modeling; vegetation studies	Vegetation/soil characteristics maintain interception, evapotranspiration, infiltration; effective impervious area is minimal	3, 4, 5
	4. Water quality is sufficient to maintain healthy aquatic, soil and vegetation communities that support biodiversity and ecosystem services	Surface and groundwater quality testing; mapping of potential pollution sources	Water quality within acceptable ranges for healthy biotic communities	6, 7
Vegetation	5. There is a diverse composition of species and vegetation types/structure	Diversity indices; qualitative estimation; LiDAR	The vegetation communities are diverse in species and type (e.g. vertical strata)	2
	6. There is a diverse age class of vegetation for self-maintenance of ecosystem structure	Visual assessment; age estimations	In each vegetation community, there is evidence of self-propagation	2
	7. Species types indicate appropriate soil moisture and nutrient regimes	Vegetation inventories / classification	Vegetation species are similar in distribution to reference areas	2
	8. Vegetation exhibits high vigour	Vegetation health assmt	Vegetation appears robust in size/morphology; no large-scale pathogenic effects	16
	9. Native (and/or desired) species communities are not threatened or dominated by invasive species	Quantitative / qualitative comparison between native/invasive species; indices of invasiveness	If introduced species are present, they do not pose an anticipated threat to the overall integrity of native/desired species	8

(Table 6.2 cont'd)

Cate-gory	Criteria	Possible Measurement Method(s)	Indications of health	Ref
Energy	10. Latent:sensible heat (Bowen ratio) is similar to pre-disturbance site characteristics, such that excessive temperature extremes are avoided.	Micrometeorological study & modeling; vegetation mapping and comparison with literature values	Vegetation cover is of a type and amount to effect evapotranspiration similar to the pre-disturbance site conditions, as is soil moisture	9
	11. Disturbances are allowed to occur or are managed for natural variability, e.g. pruning, hydroperiod, grazing, erosion/deposition, etc., to maintain adaptive renewal cycle.	Visual assessment; management protocol	Evidence of disturbance (fire scars, soil profiles, sediment deposition, vegetation condition) is similar to a reference area	11, 12, 13
	12. Excessive energy input or accumulation is not occurring (solar, chemical, litter/fuel build-up), which could cause system to 'flip' to a new stable state.	Quantification of litter/fuel accumulation; soil temperature/moisture monitoring; chemical water/soil analysis; management protocol.	Nutrient levels are similar to pre-disturbance condition or reference site; chemical fertilisers are minimised or avoided; litter/fuel accumulations are within normal range.	14, 15, 16
	13. Disturbance is of an appropriate intensity and frequency for the site and supports natural patterns of succession.	Visual assessment; aerial photography; GIS mapping	Landscape 'patchiness' and mosaics are evident similar to the pre-disturbance condition; newly disturbed areas are re-vegetating or replanted.	14
	14. System connections for information, energy flows and wildlife dispersal maintain resilience	GIS; systems analysis; modelling	Connections enable flows of beneficial information and services (e.g. wildlife corridors) but not detrimental energy (e.g. pollution via stormwater network)	25
Soil	15. Excessive erosion, deposition or soil loss is not occurring	Photopoint monitoring; stream channel cross-section msmt.; visual indicators of erosion/ deposition	No evidence of erosion/deposition, movement or soil loss; soil organic matter maintained. Land use supports soil-building and maintenance.	17, 18
	16. Plant cover protects soil from excessive heat/cold; provides source of coarse wood and/or fine litter for micro-habitat and soil decomposition processes	Biomass, canopy cover estimates; coarse wood surveys; soil temperature monitoring.	Presence of large wood, litter, stabilizing vegetation in expected amount for the site; maintenance program that leaves (some) wood and leaf litter in place	19
	17. Soil biological processes are healthy.	Biological analysis of soil	Healthy microbiotic, mycorhizzal and macroinvertebrate communities are present	20, 26
	18. Physical/chemical properties (e.g. texture, pH, salinity, permeability, organic C, pollutant levels) are appropriate for the given landscape; no excessive physical/chemical soil crusts	Physical/chemical analysis of soil	Chemical properties are similar to reference area; healthy vegetation; no obvious signs of contamination	20

(Table 6.2 cont'd)

Cate-gory	Criteria	Possible Measurement Method(s)	Indications of health	Ref
Nutrients & Elements	19. Nutrients are supplied via natural processes in levels and frequency similar to pre-disturbance condition.	Biomass/ productivity measurements; visual assessment; mapping; soil/vegetation health assessment	No excessive eutrophication of downstream water bodies. Vegetation is healthy without supplementation with chemical fertiliser.	21
	20. Nutrients are effectively cycled on-site.	Assessment of vegetation structure/ composition / heath; water quality monitoring.	Nutrient levels of off-site flows maintained near reference levels; no export of “waste” material.	22, 17
	21. Food-chain nutrient processing is occurring (e.g. grazing, predation) to redistribute nutrients in trophic levels.	Biological assessment of habitat quantity/quality	No excessive bare soil; vegetation structure similar to reference area; presence of indicator and/or keystone species	24
	22. Heavy metals and toxic compounds are not negatively affecting biota.	Chemical analysis of soil, sediment and/or biota.	Chemical constituents below accepted guidelines; sensitive indicator species are present.	6

References for Table 6.2 (assessment methods and theory):

1. Marsalek *et al.*, 2006
2. Prichard, 1998
3. Water Balance Model, no date
4. State of Washington, no date
5. Graham *et al.*, 2004
6. Karr and Chu, 1999
7. B.C. Ministry of Environment, 2006
8. Frieswyk, 2005
9. Mitchell *et al.,* 2008
10. Kleidon and Schymanski, 2008
11. Pickett *et al.*, 1989
12. Holling and Meffe, 1995
13. Middleton, 1999
14. Skinner, 2003
15. Müller, 2005
16. Carpenter and Cottingham, 1997
17. NRC, 1994
18. Ripl and Hildmann, 2000
19. Lofroth, 1998
20. Bunning and Jiménez, 2003
21. Scheffer, 2004
22. Corps *et al.*, 2008
23. Zalewski, 2002
24. Schneider and Kay, 1994
25. Janssen et al. 2006
26. Harris, 2003

6.4. Recommendations

Strategies to improve the ecological health and resilience at the site and watershed scale are based on the criteria and findings from the above analysis and previous chapters. Although the recommendations are centred on Swan Lake watershed, many should also be carried out across the region and beyond. Some strategies are not discussed here but could be important in areas not already 'built out,' including: clustered development; preserving large areas of intact native forest; limiting road density; using full-span bridges instead of culverts; preserving buffers along streams and shorelines; and preserving wetlands, headwater streams and floodplains (e.g. Schueler and Holland, 2000; Booth *et al.,* 2002). Most of these options have been foregone in Swan Lake watershed, however there are still numerous strategies that can be deployed to improve ecological health and resilience.

1. Address mismatches in scale with better information and management

As discussed above, there is currently no institutional body or group focused on managing or monitoring Swan Lake watershed (nor the parent watershed, Colquitz Creek); indeed, only one watershed in the core area of the Capital Regional District is currently the subject of active management by a multi-stakeholder organisation (Bowker Creek watershed). Thus long-term flow records, water quality data and indices of terrestrial ecosystem health are absent, preventing feedback between land use and policy, as outlined in Figure 6.8. Such information could be used (for example) to identify hotspots for pollution and nutrient loading, so that management can be targeted to these areas. In order to improve this situation, the following is recommended:

- Continuous water quality and flow monitoring is needed at a number of points in stream channels in the watershed, along with periodic water chemistry sampling. Flow data are critical in order to calculate loading rates (which provide far more valuable information than simply concentrations, as discussed in Chapter 5), and would enable calculation of hydrological indices of flashiness and other parameters as a surrogate for ecological resilience. Simple and inexpensive devices such as those used in this study could be deployed to monitor stream discharge. A benthic invertebrate monitoring program (B-IBI, e.g. Karr and Chu, 1999) would also be valuable.

- Water quality monitoring in Swan Lake is needed, including phytoplankton studies to monitor chemical and biological conditions (P. Lucey, pers. comm.).
- An urban forest inventory is needed to assess the diversity, age and health of the treed areas in the watershed. A recommended method for this study is the Urban Forest Effects Model (UFORE, www.ufore.org), a method developed by the US Forest Service, that includes estimates of ecosystem services including carbon sequestration and air pollution removal (Townsend and Hegg, In Progress). As discussed in Chapter 5 and above, the urban forest is critical for watershed functions including interception and evapotranspiration of precipitation (reduction of runoff volume) and climate cooling.

2. Vegetation planting and management to improve water and energy imbalances

Widespread restoration of native vegetation and implementation of "green infrastructure" is required to intercept more precipitation and direct water through the 'green' portion of the water cycle, thereby improving solar energy dissipation, reducing the 'flashiness' of stream flows and improving water quality, as discussed above.

A readily apparent opportunity to restore some amount of the pre-development vegetation community is in the Swan Lake wetlands (e.g. with native willow, as demonstrated in Appendix D). In most other areas of the watershed, however, the original forested ecosystems cannot be replaced given the current land use. Therefore, vegetation should be integrated into the urban landscape to the degree possible, in part by constructing *multi-functional landscapes* with "green infrastructure." Examples of green infrastructure include nature parks, constructed wetlands, rain gardens, bioswales, green roofs and permeable pavement (US EPA, 2008b). Green infrastructure helps to confer resilience by keeping water on the land, thereby dissipating solar energy through evapotranspiration; furthermore, water quality is improved with filtration and uptake by plants, improving downstream ecosystem health, and by retaining and slowing surface runoff, stream channel function is supported. Systems can be designed for multiple benefits, including purifying stormwater, sequestering carbon, mitigating air pollution, cooling the climate and providing aesthetic and other social benefits (e.g. traffic calming). The Seattle SEA Streets project offers an excellent example; in this case, the city has narrowed residential roads and installed linear rain-gardens containing a variety of native vegetation along each side of the right-of-way; results have included a 98% reduction in total runoff volume, substantial water quality improvements and increased property values (Seattle Public Utilities, no date). I estimated that by carrying out a similar retrofit, at least about 36 hectares of land would be available for such structures in Swan Lake watershed (Figure 6.12; data not shown). Other areas that could be targeted for vegetation planting include portions of school grounds and playing fields as well as green roofs. Green roofs are effective for reducing stormwater runoff, for reducing building cooling and heating needs and for growing food and other social uses (Oberndorfer *et al.*, 2007; City of Portland, 2008). They also help mitigate the urban heat island effect through evaporative cooling; green roofs are generally between 25ºC and 17ºC cooler than standard roofs (Alexandri and Jones, 2008; Takebayashi and Moriyama, 2007).

Figure 6.12. Example of a typical residential street boulevard in Swan Lake watershed (left), as it might look retrofitted with rain-gardens (Seattle SEA Street; right)

3. Stream Restoration and Water Balance

As discussed in Chapter 3, stream channels may exhibit alternative stable states, while land use and management can alter the phase-space landscape, making either state more or less likely. The objective for restoring healthy streams is to increase the likelihood (the size of the basin of attraction) of the PFC state. As shown in Figure 6.13, in the un-restored urban watershed, the degraded state has a higher probability of occurring, whereas in a 'restored' condition, the healthy (PFC) state has higher resilience.[17] In order to improve stream channel function, two interrelated aspects of restoration are represented diagrammatically. Direct restoration of stream channels at the site scale is required to re-establish floodplain accessibility, native riparian vegetation and to slow flows, as discussed in Chapter 3. This would increase the resilience of stream channels to the disturbance of erosive flows. However, as discussed in Chapter 5, it is also important to address watershed scale disruption of the water cycle (i.e. by reducing surface runoff) in order to increase the viability of restoration measures and to improve water quality (Walsh *et al.,* 2005). This entails reducing the resilience of the nonfunctional state. Stormwater management practices based on mimicking the natural water cycle are becoming widely adopted in communities across North America and in the Pacific Northwest, in order to address widespread degradation of water quality and stream channel habitat in urban areas (Podolsky and MacDonald, 2008; Denzin, 2008). There are a wide variety of strategies available for both new developments and retrofit applications (e.g. Schueler and Holland, 2000), for example using 'green infrastructure,' as described above. Stormwater management needs to be implemented at the range of scales shown in Figure 6.7. For example, at the scale of a “roof shingle,” appropriate plant species selection on green roofs is important, while at the lot scale, rain gardens can be used to retain and infiltrate roof runoff; at the neighbourhood scale, measures may include subdivision layout and narrow roads to limit impervious areas, as well as roadside swales and permeable surfacing.

Focusing on both restoration and water management entails treating the “cause” of

17 For more description of transition-state diagrams, see Chapter 1 and Walker *et al.,* 2004.

impaired health (disrupted water cycle) as well as the "symptoms" (degraded stream channels). Although stream restoration opportunities are challenged in many areas of the watershed due to adjacent land use, in Chapter 3 some possibilities were highlighted. Furthermore, daylighting (opening channels that are presently enclosed in culverts) should be considered when re-development and infrastructure upgrading is carried out; this would apply to the enclosed sections of Blenkinsop Creek, as well as to smaller tributary channels.

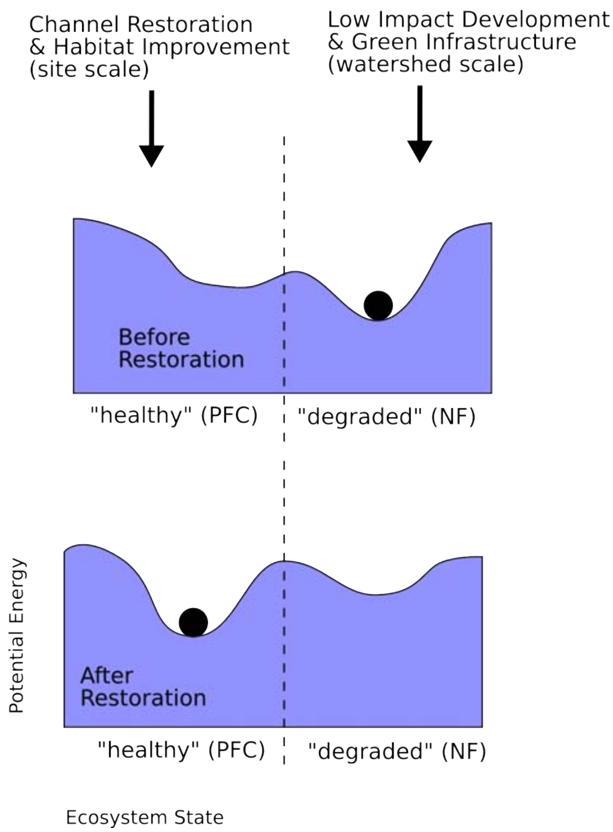

Figure 6.13. A dual scale focus is required for effective restoration of watershed resilience; the site scale includes channel restoration, while the watershed scale includes minimising runoff with green infrastructure

(image by the author)

4. Nutrient/pollution management to reduce loading, eutrophication and sedimentation of water bodies

As discussed in Chapter 5, nutrient levels flowing into Swan Lake and downstream into Colquitz Creek are a serious concern for contributing to eutrophication, and maintaining an undesired state. Prior to initiating interventions to the lake itself, it is critical to reduce nutrient loading (Scheffer *et al.,* 2002). Mineral loading to Swan Lake and downstream of the lake is also high, indicating a high rate of "ecosystem ageing," i.e. depletion of soil fertility in the watershed. Since the riparian areas in the watershed are in such poor condition, they are likely ineffective in removing nutrients, therefore a distributed approach to nutrient and non-point source pollution management in the watershed is required (Cadenasso *et al.*, 2008). This requires reducing direct flows to watercourses and effecting more filtration through vegetation and soils.

Agriculture is likely one of the most important sources of nutrient runoff, particularly since floodplains are cultivated with annual crops, exposed soil is flooded seasonally, and there are few riparian buffers along watercourses in agricultural areas. Therefore economic incentive programs are needed to encourage farmers to establish buffers along agricultural watercourses, and to adopt "stream-friendly" cultivation techniques; this could operate at the provincial, regional and/or municipal level. These types of programs have been shown to be effective for improving water quality and habitat, for example in Ontario and Australia[18].

Another strategy for managing nutrients in agricultural areas would be to encourage cultivation of short-rotation woody crops (SRWC) such as willow in floodplain areas and marginal farmland susceptible to flooding. This type of program has been implemented in Poland and other areas specifically for improving fresh water quality, since with rapid growth rates willow can effectively take up nutrients and pollution (Zalewski *et al.*, 2003). Willow has been proven in Sweden and in Europe as an efficient source of energy for combustion in district heating and electrical plants; it is also a viable strategy for carbon sequestration, and for phytoremediation (Kuzovkina and Quigley, 2005; Grelle *et al.,* 2007). Because it is a perennial crop that repeatedly sprouts from cut stumps, there is negligible soil disturbance required to plant and harvest the crop, and the roots bind soils and prevent erosion (Börjesson, 1999a). A study in Ireland showed the economic benefits of growing SRWC exceeded most other agricultural land uses with the exception of dairy

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18 Personal communications with senior staff with the Grand River Conservation Authority and the Southern Rivers Catchment Management Authority, as part of a paid contract for the Capital Regional District (Townsend, 2006).

farming (Styles *et al.,* 2008). District heating plants are not yet used in Victoria, but they have been proposed as part of a distributed system of waste ("resource") management (Corps *et al.*, 2008)[19], and are encouraged by the provincial government as an energy-efficiency strategy (Province of BC, 2007b). Currently, a leading-edge mixed use development in Victoria incorporates an electrical/heat combustion system using forestry wood waste and biosolids; this may provide a market for some amount of SRWC. High-quality treated wastewater discharged from small scale sewage treatment plants could help to augment low summer base flows in Blenkinsop Creek and provide a source of clean water to help flush nutrients through Swan Lake in the summer when drawdown is very low (Chapter 5). Willow could also be planted alongside the inflow stream to Swan Lake in the form of constructed wetlands, to provide some cleansing of water in Blenkinsop Creek. The shrubs should be harvested periodically (even in the absence of a market for the wood), to maximize nutrient and pollutant removal from the system.

5. Public education about watershed processes

There are currently no estimates of the level of public awareness about watershed ecology in the study area, however, since there are no public education campaigns focused on this topic, it may be assumed to be relatively low.[20] The Swan Lake Christmas Hill Nature Centre provides educational programs, mostly to children and via displays in the nature centre; some watershed information is provided, for example a 3 dimensional watershed model was recently constructed, however most information relates to ecosystems and wildlife in the sanctuary itself. The largest land use in the watershed is residential property, therefore encouraging stewardship and low-impact practices at the single property scale has a large potential benefit, particularly for water quality (Schueler, 2000). Behaviours that affect watershed health include lawn care, car washing and driveway cleaning, septic system maintenance, garden practices and car

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19 The strategy proposed for this area by Corps et al. (2008), in answer to the mandate by the province of B.C. for Greater Victoria to implement sewage treatment, would see up to 32 small ('house-sized') sewage treatment plants across the region capable of providing electricity and heat to local neighbourhoods, with potentially very large economic benefits.

20 A survey of residents of the watershed could be undertaken to address this uncertainty.

maintenance. Public education needs to be carefully targeted however, and ideally should use a variety of media (Schueler, 2000). Ideally, a watershed stewardship group should be formed, that would help to promote best management practices in the watershed and carry out restoration activities.

6. Ecosystem Valuation

Swan Lake watershed has been subject to fairly typical urban development patterns and processes, whereby social and economic priorities have trumped ecological health. One way to address this problem, and to prevent it in other developing areas, is to explicitly value ecosystem services. Although the methods used to value complex ecosystem functions may be critiqued on individual merits, valuation in general can help to highlight the important benefits derived from healthy ecosystems, enabling decision makers to consider the potential long-term consequences of ecosystem destruction or degradation undertaken for economic goals (e.g. Daily *et al.*, 2009). Some of the ecosystem services that are typically subject to valuation include carbon sequestration/storage, recreational opportunities, air pollution removal, water purification, pest control and biodiversity (Costanza *et al.,* 1997). In more developed areas, the current ecosystem value should be contrasted with historic or pre-development values, to highlight the value of what has been lost; the objective of such an analysis would be to use this comparison as a context within which to restore functions, and to avoid the problem of the slipping baseline (Hegg, 2009).

7. Government policy and developing institutional capacity to support watershed health

There is currently no provincial legislation or body that undertakes integrated watershed planning; rather, many ministries oversee isolated aspects of development and resource management within watersheds (Brandes and O'Riordan, 2007; West Coast Environmental Law, no date). However, the provincial Living Water Smart Plan places a high importance on healthy streams and watersheds (Province of B.C., 2008). Small urban watersheds may fall within the jurisdiction of local governments, but provincial funding and support is still required to enable planning at this scale. For example, the State of Washington has a Watershed Planning Act (enacted in 1998), that recognises the importance of local planning and requires reporting to the state legislature regarding the status of watershed planning activities (State of Washington Department of Ecology, no date). This program, as well as others such as the Orgeon Watershed Enhancement Board and the Saskatchewan Watershed Authority, should be reviewed by provincial policy makers.

Furthermore, provincial funding is required to encourage adoption of integrated rainwater management by local governments. Green infrastructure, as described above, has the potential to improve multiple aspects of watershed health.

Management and planning also need to take into account the terrestrial energy balance, which is closely tied with climate change. The B.C. Provincial government currently has a strong focus on mitigating climate change, however to date most policy is directed toward emissions reductions (Province of B.C., 2007a). A focus on maintaining and enhancing ecological resilience will enable better adaptation to existing and future climate and weather events. The provincial government could therefore provide increased funding to urban forestry initiatives and urban ecosystem management and planning as a climate mitigation/adaptation strategy.

The municipality also needs to develop plans for monitoring and watershed management and to commit to watershed stewardship and stringent requirements for low impact development in urban planning, in order to follow up on its successes for demonstrating leadership in some of these areas (Rutherford, 2007).

The municipality has a policy for new developments to require a certain percentage of the development to be dedicated as park land. However, the municipality is already challenged to manage its existing parks, therefore one strategy could be to accept payment in lieu of land dedication from developers, and to apply these funds to create and manage larger parks that also function as healthy ecosystems, for example the possible wetland restoration or stream daylighting as proposed above.

Other Research Needs and Opportunities

There is a critical lack of information about watershed scale processes, regarding this and other local urban watersheds. Some suggestions were provided at the beginning of this section, including long-term flow monitoring and water quality monitoring, as well as urban forest studies. Additionally, the following would provide valuable information for increased understanding of urban ecosystem function and for improved management of watershed health.

- More detailed vegetation inventories and studies at both the site scale (Swan Lake Christmas Hill Nature Sanctuary and other remnant natural areas) and at the watershed scale, e.g. field surveys (in permanent plots) and GIS mapping, and urban forest inventories.
- Additional paleoecology studies to better understand past vegetation communities and local influences of past climate change. For example, the early Holocene experienced higher temperatures than today, and the plant communities present at this time could help to define restoration objectives for anticipated temperature increases with climate change (R. Hebda, pers. comm.).
- Social studies (e.g. surveying via questionnaires) of residents in the watershed, evaluating knowledge of ecological issues and behaviours that affect watershed health; this could be carried out by university/college students and/or stewardship groups (e.g. POLIS, Habitat Acquisition Trust) and could be used as baseline information and re-evaluated after education programs are implemented, to measure their effectiveness.
- Long-term hydrological monitoring of hydrographs and water quality should be carried out in a partnership between Swan Lake Christmas Hill Nature Sanctuary and the University of Victoria (e.g. Geography and/or Environmental Studies Departments). High schools and community groups could be involved in water

quality monitoring. It is important to design a long-term program for monitoring, since many years of data are required to develop some of the hydrological indices discussed above.

- Micrometeorology studies and modelling to examine the extent of urban heat island effect in the study area and to examine opportunities for mitigating this effect with urban 'greening' (vegetation planting and green infrastructure). There is currently an array of weather stations deployed at local schools (Weaver and Wiebe, 2006), however radiation and latent/sensible heat indices are not part of the data collected, which is necessary for energy balance calculations. Energy data from urban stations could be compared with stations set up in nearby forested, wetland areas and agricultural areas. Thermal imagery is another technique that is used in some areas to identify urban "hot spots" and to target these with vegetation planting (Lo *et al.,* 1997; Weng, 2006). Modelling programs are also available that integrate the energy and water balance in order to support urban planning that addresses these functions of the landscape (e.g. Mitchell *et al.*, 2008; ENVI-met, 2008).

In order to develop these recommendations into effective management strategies, the next step will be to engage a multi-jurisdictional and interdisciplinary group (e.g. resource managers at Swan Lake Christmas Hill Nature Sanctuary, local government, First Nations, the general public, and scientists in various fields). Ideally, this group would work with a system designed to address the multiple scales discussed above (e.g. Resilience Alliance, 2007a, 2007b), and utilize scenario planning to work toward desired (and scientifically based) goals for improving ecological health and resilience in this watershed.

6.5. Conclusions

As an urban ecosystem, Swan Lake watershed is a complex adaptive system (Liu *et al.*, 2007), and indices of ecological resilience at this scale are lacking. For this reason, I considered processes occurring at a variety of scales, from the site (e.g. wetland vegetation species composition) to the landscape (e.g. tree cover across the watershed), and from the instantaneous (e.g. loading rate) to the century time scale (e.g. land clearing).

The following research questions are revisited in light of the findings of the previous chapters.

Research Question 1: Based on available information, what were the main ecological attributes and processes in Swan Lake watershed in the past? How did people manage and interact with them?

This question was addressed with a detailed review of landscape history and a paleoecological study. Prior to European settlement, the landscape around Victoria, including Swan Lake watershed, consisted of a mixture of Garry oak (and prairie/savannah) ecosystems and conifer forests, interspersed with numerous wetlands and riparian corridors. Salmon spawned in Colquitz Creek and Swan Creek; Swan Lake had clear water capable of supporting native trout. The landscape was inhabited and actively managed by indigenous people for over 4000 years, using fire and various cultivation techniques. Europeans initiated large-scale land disturbance, beginning in the mid-1800s, with forest clearing, agriculture and transportation infrastructure. By around the turn of the 19th century, native vegetation was largely cleared, many wetlands were drained, and by the 1920s several streams in Swan Lake watershed had been channelized. Swan Lake itself was subject to pollution from sewage and winery effluent for over 40 years. This land use precipitated a number of changes in the watershed ecosystems. One of the most obvious effects was a shift in Swan Lake to turbid water, algae blooms and anoxic conditions, due to nutrient loading. Other effects included reduction of stream channel complexity and habitat, loss of terrestrial ecosystems and disruption of the water cycle.

Research Question 2: How do components of Swan Lake watershed function today, according to vegetation and water-related studies? How do these studies help to

evaluate ecological health and/or resilience?

This question was addressed with field and map-based studies of vegetation, stream channel and lake characteristics, and hydrology, to characterise existing watershed processes. These indices were chosen since water and vegetation together control or mediate a large proportion of energy and nutrient cycling at both the watershed and site scale, while stream channels and lakes receive runoff and therefore integrate landscape level disturbances.

According to a “Proper Functioning Condition” (PFC) assessment, the majority of the streams assessed were “nonfunctional” or “functional at risk,” as they lacked the physical features necessary to dissipate the energy of high flows, and to provide important ecosystem services. The main causes for degradation were past channel modification and changes to the runoff characteristics in the watershed, which serve to erode the resilience of the healthy (PFC) state.

At the watershed scale, a very small percentage of the original conifer forest and Garry oak (and prairie/savannah) ecosystems remains, while impervious surfaces, grass and agricultural crops are now the dominant land cover. Rainwater is conveyed to stream channels and lakes via storm drains, with little retention or infiltration. These changes contribute to pollution and nutrient and sediment loading to downstream waterbodies, and increased flashiness and stream channel erosion. The watershed is over-connected hydrologically, which reduces resilience to disturbances (e.g. toxic spills and high rainfall events).

At the wetland scale (Swan Lake Nature Sanctuary) a large area was cleared of native woody vegetation and is now dominated with reed canarygrass. The remaining shrub community contains a high proportion of invasive herbaceous species compared to nearby reference sites. The persistence of the grass over several decades suggests it entails an alternative stable state, therefore management interventions may be required to restore a native community. A method using willow plantings and mulch to 'shade out' reed canarygrass was therefore tested in a pilot project, with positive results (Appendix

D).

Stream gauging indicated that Blenkinsop Creek is highly "flashy," reacting practically instantaneously to rain events, probably due to impervious areas and culverts; this contributes to degraded channel conditions and poor water quality, i.e. reduced resilience in both the stream channel and the lake. Swan Creek (at least in the upper reaches) is much less flashy, due to the hydrological buffering effect of Swan Lake, suggesting greater resilience and a better chance of success for restoration. Indices of flashiness could be used to characterise resilience, however longer-term flow data is required. Lake levels in Swan Lake also vary more widely compared to a reference lake in an undeveloped watershed. This is likely due to similar factors as flashiness in the streams; pronounced drawdown in the lake over the summer may also be related to channelization of the outflow stream which used to entail a large wetland. Restoration of this wetland is feasible as it is included in publicly owned land, although the current land use as allotment gardens would need to change; this would greatly improve habitat and water quality in Swan Creek and in downstream areas (Colquitz Creek and Portage Inlet). Hydrology and water quality data indicate impaired ecological health.

In summary, based on a comparison with the historical inquiry, I inferred several changes in ecosystems according to an alternative stable state model: from clear water in Swan Lake to turbid water; from native-vegetation-dominated to cleared with high impervious surface cover, across the watershed; from woody vegetation-dominated to grass-dominated, in Swan Lake wetlands; from functional (healthy) streams to nonfunctional streams that served mainly as conduits for moving water off the land. Ecological resilience for the former states was eroded and now many components of the watershed exist in alternative stable states defined by a new set of conditions and relationships.

Research Question 3: ***Based on the findings of the study, how could ecological health and resilience be assessed in an urban watershed? Is Swan Lake watershed healthy and resilient to disturbances according to these criteria?***

Ecological health was defined as:

The development of ecosystem structures, functions and composition that serve to dissipate energy gradients, within a cycle of adaptive renewal consistent with the historic range of variability, where resilience is maintained around a desired stable state.

This definition combines several established bodies of research (energy dissipation based on non-equilibrium thermodynamics; ecosystem “development”; and resilience theory, entailing cyclical succession, periodic 'release' of bound energy and alternative stable states). Since there is no existing set of well established indicators, I proposed a set of criteria under five categories (water, vegetation, energy, soil and nutrients/elements) to assess ecological health, wherein resilience is embedded.

Specifically, some possible indicators of watershed-scale resilience include:

- water quality, which is an indicator of larger scale watershed processes such as erosion and pollution, and that may also indicate the degree of “ecosystem ageing,” i.e. loss of nutrients and cations from the landscape;
- vegetation cover and composition at the watershed scale as an indicator of the function of the “green water cycle,” with mapping and urban forest inventories;
- surface energy balance, indicated with micrometeorology, to quantify sensible and latent heat and the degree of solar energy dissipation, which helps to create a hospitable climate and supports other ecosystem processes;
- surface water flows, represented in hydrographs (and indices of flashiness) from stream and lake gauging, which help to illustrate watershed scale runoff and other indirect effects of land use changes.
- network connectivity, using systems modelling and GIS to examine linkages between watershed ecosystems and drainage patterns.

The findings of this study and general estimates were used as a preliminary assessment of ecological health and resilience, suggesting that Swan Lake watershed has impaired ecological health and is not resilient to disturbances such as extreme climate/weather events.

Research Question 4: How might Swan Lake watershed be managed in the future to

support and/or restore ecological health and resilience?

In order to support ecological health and resilience, future management should focus on mimicking the hydrological function and energy balance of the pre-development conditions. This requires better information and management that enables feedback loops between ecological conditions and planning and management interventions, e.g. hydrological monitoring, vegetation inventories, best practices and restoration incentives. Vegetation forms a critical component of watershed health, therefore existing forests and wetlands need to be protected, and planting needs to be carried out across the landscape. Due to limited land for planting, “multi-functional” green infrastructure needs to be implemented, such as rain-gardens planted with native woody species that serve multiple functions. Stream restoration is required in order to shift the streams from a “non-functional” to a “properly functioning” condition, however rainwater and runoff must be managed at the watershed scale in an integrated fashion, and at a wide range of scales, in order to address one of the root causes of channel degradation. Nutrients and pollution also need to be better managed, to prevent eutrophication and toxic effects on streams, lakes and the marine environment. Recommended strategies include establishing buffers along watercourses in agricultural areas, and providing farmers with incentives for doing so, retaining and filtering surface runoff, and using short-rotation woody crops for phytoremediation as well as for bioenergy. The public needs to be made more aware of watershed processes to encourage personal stewardship behaviour and support for ecological restoration. Ecosystem valuation can be used as one tool for this purpose, to highlight the importance of ecosystem services in maintaining human health and quality of life. Government support is also required, to provide support for programs to deliver the above recommendations.

Conclusion

The overall thesis hypothesis addressed in this study was: ***Urban development and land use patterns in Swan Lake watershed have degraded ecological health and resilience***

over the past 150 years, as evaluated through history, hydrology and vegetation studies.

This hypothesis is supported by findings of this study, as shown by the various systems models, and analysis using the set of proposed criteria. Development in Swan Lake watershed has generally been carried out to serve human needs, at the expense of ecological systems, and has resulted in a highly rigid landscape, for example due to loss of vegetation, a high proportion of impervious surfaces and high surface runoff. These qualities entail a loss of important ecosystem services and reduced energy dissipation, e.g. of hydrological and weather/climate disturbances. An investigation of the pre-development characteristics of the watershed, combined with present day studies, supported the above hypothesis.

More integrated approaches to urban watershed management are needed, to account for complexity and interactions between people and other organisms, ecosystems and the nested structures and processes within each. Systems theory and in particular resilience theory provide one approach that may help to bridge the divide between social/economic and ecological theory. This integration is critical to address the scale and complexity of global problems. Urban ecosystems provide the ideal context for addressing these problems since they represent both opportunities for education and the crux of the problem in the form of a concentrated human population.

A proposition was advanced alongside the thesis hypothesis:

It is further proposed that ecological health and resilience can be supported and/or restored by emulating the pre-development landscape function.

This proposition stems from a recognition that current land use and development patterns are unsustainable, since global ecosystem degradation is at a critical level, as discussed in Chapter 1. This study outlined general principles for the fundamental shift that is required to move from current practices toward development patterns that increasingly support, rather than degrade, ecological health. Thus the proposition can be tested as a hypothesis with increased evaluation of the ecological effects of low impact development practices. The five-processes assessment developed here provides a framework to support this effort, as it can be used as both an assessment and a design tool.

Global assessments of ecosystem health and climate change indicate critical systems failure may not be far off (e.g. Hassan, 2005; IPCC, 2007; Steffen *et al.*, 2007). This highlights the importance of managing local ecosystems for ecological resilience, in order to sustain ecosystem services at a scale relevant to a post carbon future, as well as to provide support and beneficial feedback to larger scale processes.

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Appendix A - Summary of Paleoecology Study at Swan Lake

Title: Examination of near-surface pollen and macro-fossils in disturbed urban wetlands on southern Vancouver Island, used to establish a basis for restoration

Authors: Lise Townsend and Richard Hebda[21]

Publication: In Preparation for submission to Restoration Ecology (Fall 2009**)**

Abstract: Peat samples were collected from two wetlands (Swan Lake and Burnside Rd.) in Saanich, B.C., and historical records were examined, in order to characterise the pre-disturbance wetland vegetation community at the sites and establish reference conditions and possible restoration objectives. *Phalaris arundinacea*, which current dominates the Swan Lake site, is a highly invasive species regionally and represents a biological barrier to restoration. It is a minor species at the Burnside site, thus the two different sites (supplemented with a summary of paleoecological studies of other local sites in the literature) are used to inquire if it was present in the past or only associated with cultivation. A variety of agricultural disturbance indicators were observed at both sites, at various depths, however in one of the study locations at Swan Lake where a distinct disturbance horizon could be distinguished, *Phalaris* is lacking in the pollen record. The results suggest that *Phalaris* plant communities are a recent phenomenon associated with cultivation and disturbance. Pollen assemblanges immediately below the Phalaris zone show that wetland types across this limited geographical area were diverse, and at Swan Lake dominated by willow (*Salix* spp.) and other woody species. Disturbance and crop species pollen indicators were present at varying depths, thus other impacts of intensity and depth of disturbance (soil enrichment, oxidation, etc.) can be inferred and may challenge restoration efforts. The pre-disturbance native plant communities elucidated through this study can be used as restoration targets, provided limiting factors can be managed.

Methods

21 Curator, Royal British Columbia Museum (Victoria B.C.) and Adjunct Professor, University of Victoria

Peat samples were examined for general characteristics and macrofossils at 12 sites in the wetlands surrounding Swan Lake, by coring the peat with a manual stainless steel Hiller side-filling corer. High-resolution pollen samples from near the surface were obtained from blocks of peat dug out by shovel, from two sites on the southwest and northeast sides of the lake, both located in a monotypic *Phalaris* community. Macrofossils and peat characteristics of selected samples were examined at the Royal B.C. Museum palynological laboratory using a dissecting microscope (Martin and Barkley, 2000; Warner, 1990; Lévesque *et al.,* 1988), and pollen samples were prepared using standard methods (Moore *et al.*, 1991). Pollen was treated chemically and samples were mounted with transparent gelatin on a glass microscopic slide, and examined at 400x and 1000x magnification with a light microscope. Pollen was identified to the family or genus level (depending on the pollen type) with the aid of published references (Moore *et al.*, 1991; Moore and Webb, 1978; Kapp *et al.*, 2000). Pollen data were tabulated in Microsoft Excel, and then plotted diagrammatically using PSIMPOLL, version 05.02.08 - 4.26 (Bennett, 2005).

Results

Generally, peat containing abundant plant material (and in some cases, wood) characterised the top of the deposit, while lower layers consisted of limnic peat and *gyttja*[22] of various thickness; *marl*[23] was observed at all sites underlying those layers, and finally marine clay marked the bottom of the peat deposits, which ranged from 2m to over 8m at one site. At several sites where peat macro-fossils were examined, seeds of water parsley (*Oenanthe* sp.), water hemlock (*Cicuta* sp.) and pond lily (*Nuphar* sp.) were observed at various depths below about 40cm.[24]

At the south site (1g), grass pollen was very abundant in the upper layers, and declined to almost no grass in lower layers (Figure A1). At the north site (1Ah), more agricultural

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22 *Gyttja* is “a nutrient-rich sedimentary peat consisting mainly of plankton, other plant and animal residues, and mud....deposited in water in a finely divided condition” (Government of Canada, 2001).

23 *Marl* is a white-ish, soft deposit formed in mineral-rich environments (Hebda, Pers. Comm.).

24 These are some of the more readily identified and typically well preserved seeds.

disturbance had occurred to a deeper level, however a similar trend was evident. Pollen of large cereal grains found at site 1Ah along with weedy species also confirmed more intensive agriculture was practiced there.

Willow was a major component of the pollen assemblage at both sites, and in general increased with depth in the profile, thus it was clearly one of the dominant pre-disturbance wetland species. Other species co-occurring with willow included: red alder (*Alnus rubra*), skunk cabbage (*Lysichiton americanus*), species in the rose family (Rosaceae), cattail (*Typha* sp.) and Cyperaceae (sedge/rush). Other wetland species identified included Apiaceae (e.g. *Oenanthe, Cicuta*), cedar-type pollen (Cupressaceae, most likely *Thuja plicata*) and red alder (*Alnus rubra*), with small amounts of *Menyanthes,*[25] *Nuphar* and *Myrica*.

Discussion/Conclusions

There is lingering debate in the botanical community whether reed canary grass (RCG) is a true exotic invasive species in the Pacific Northwest, or if it is an aggressive strain of a native species (Merigliano and Lesica, 1998). RCG is undisputedly invasive in certain circumstances, tolerates a wide degree of nutrient and soil moisture conditions, and has consequently been associated with reduced biodiversity due to competitive exclusion of other species (Zedler and Kercher, 2004; Perkins and Wilson, 2005). Therefore it is often the target of control strategies, however these strategies are frequently unsuccessful and expensive (Hovick and Reinarrtz, 2007). In this study, I established that reed canarygrass is a recent dominant of the wetland vegetation community, likely deliberately introduced as a fodder crop, and/or favoured along with land disturbance associated with agriculture, whereas the pre-disturbance vegetation community was dominated by willow and included a diverse array of herbaceaous species. This information is valuable to restoration and management planning.

25 *Menyanthes* is included in a historical species inventory at Swan Lake (Shepherd, 1975) and in a herbarium sample at the Royal B.C. Museum, dated 1890 and 1897 (sample #4-1167 and # 3949, respectively), but has not been observed at the site in recent years.

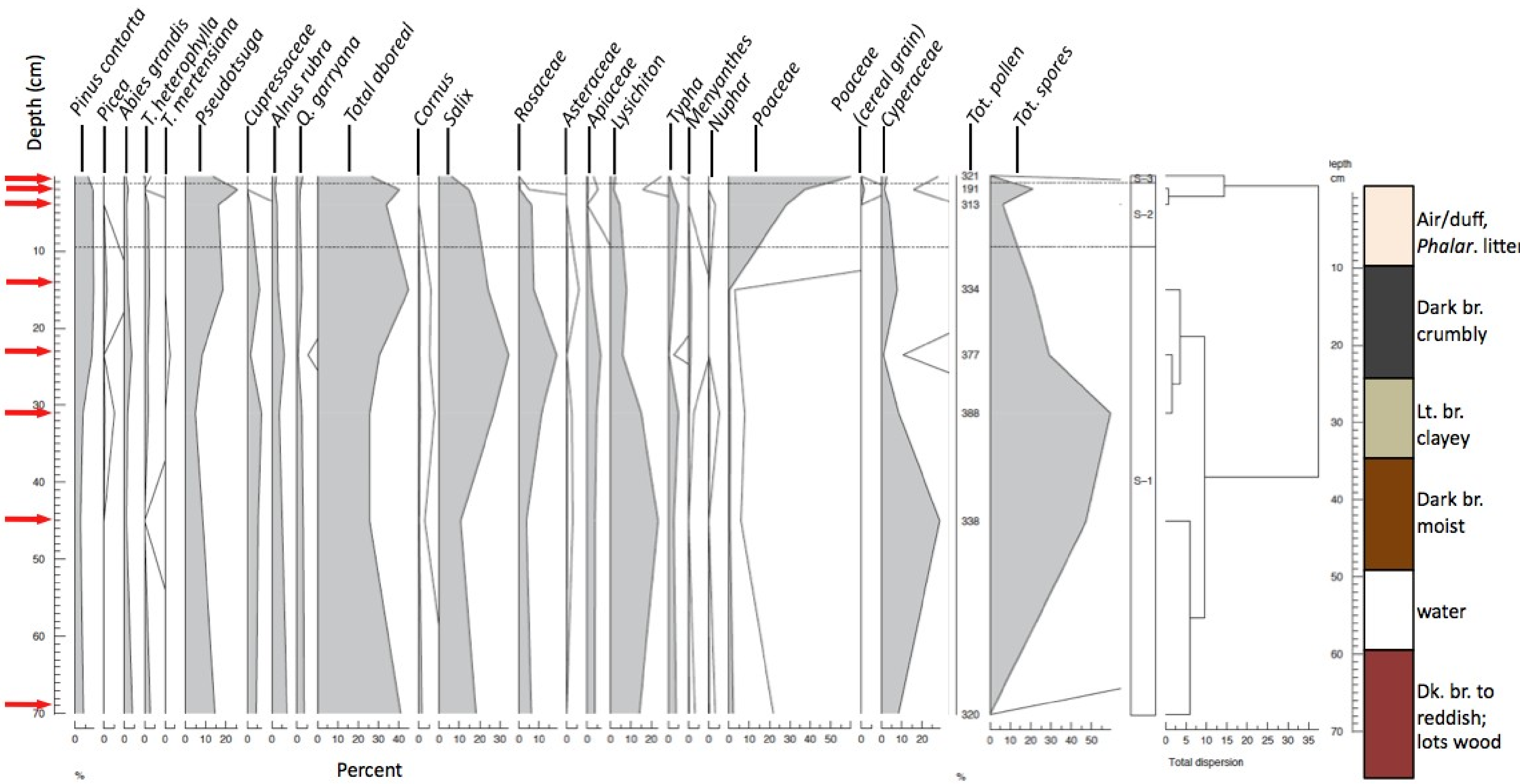

Figure A1. Pollen diagram showing stratigraphy and composition of upper 70cm of peat at Site 1g, Swan Lake (arrows indicate depths at which samples were taken)

Appendix B - Proper Functioning Condition Definitions and Photographs

Definitions (USDI, 1993)

Capability - The highest ecological status a riparian-wetland area can attain given political, social, or economical constraints. These constraints are often referred to as limiting factors.

Potential - The highest ecological status an area can attain given no political, social, or economical constraints; often referred to as the "potential natural community" (PNC).

Proper Functioning Condition - Riparian-wetland areas are functioning properly when adequate vegetation, landform, or large woody debris is present to dissipate stream energy associated with high waterflows, thereby reducing erosion and improving water quality; filter sediment, capture bedload, and aid floodplain development; improve flood-water retention and ground-water recharge; develop root masses that stabilize streambanks against cutting action; develop diverse ponding and channel characteristics to provide the habitat and the water depth, duration, and temperature necessary for fish production, waterfowl breeding, and other uses; and support greater biodiversity. The functioning condition of riparian-wetland areas is a result of interaction among geology, soil, water, and vegetation.

Functional—At Risk - Riparian-wetland areas that are in functional condition but an existing soil, water, or vegetation attribute makes them susceptible to degradation.

Nonfunctional - Riparian-wetland areas that clearly are not providing adequate vegetation, landform, or large woody debris to dissipate stream energy associated with high flows and thus are not reducing erosion, improving water quality, etc., as listed above. The absence of certain physical attributes such as a floodplain where one should be are indicators of nonfunctioning conditions.

Figure B1. Swan Creek, Reach 2, showing eroded channel and trampling ("non-functional")

Figure B2. Swan Creek, Reach 6 ("PFC")

Figure B3. Swan Creek, Reach 8, allotment gardens during flood ("non-functional")

Figure B4. Blenkinsop Creek, Reach 1 (above) and Reach 3 (right), both "non-functional"

Figure B5. Blenkinsop Creek, Reach 4 at Galey Farms (PFC)

Appendix C - Vegetation Inventories and Study Data

Table C1. Swan Lake wetland vegetation inventories from 1973 and 1975 (Shepherd, 1975; Zaccarelli, 1975), with possible extirpated species highlighted

Scientific Name	Common name	Obs. by L. Townsend in 2006-2008 (x)
Salix babylonica	weeping willow	x
Salix lasiandra	red willow	x (Salix lucida ssp. *lasiandra)*
Betula sp.	birch	x (*B. papyrifera*; planted 1999 in Leeds Cr. area)
Crataegus douglasii	black hawthorn	x
Salix spp.	willow	x
Spiraea douglasii	western spiraea	x
Cornus stolonifera	red osier dogwood	x
Lonicera involucrata	black twinberry	x
Pyrus fusca	Pacific crabapple	x (near E wharf)
Rosa nutkana	common wild rose	x
Alisma plantago-aquatica	water plantain	
Sagittaria cuneata	wapato	
Scirpus sp.	bulrush	x (Schoenoplectus lacustris)
Glyceria grandis	American mannagrass	
Phalaris arundinacea	reed canarygrass	x
Sparganium eurycarpum	broad-fruited bur-reed	x (*Sparganium* sp., near outlet stream; rare)
Sparganium racemosum	bur-reed	
Typha latifolia	broad-leaved cattail	x
Lysichiton americanum	yellow arum	
Lemna minor	lesser duckweed	x (*Lemna* spp.)
Lemna triscula	ivy-leaved duckweed	
Spirodela polyrhiza	greater duckweed	
Wolffia sp.	watermeal	
Polygonum amphibium	water persicaria	x (in wetlands away from shore)
Nuphar polysepalum	yellow water lily	x
Nuphar varigatum	bullhead lily	
Ceratophyllum demersum	hornwort	
Potentilla palustris	marsh cinquefoil	
Cicuta douglasii	western water hemlock	x (near Rainbow St. inflow stream; rare)
Oenathe sarmentosa	water parsley	x
Menyanthes trifoliata	buckbean	
Solanum dulcamara	bittersweet nightshade	x
Mimulus guttatus	common monkey-flower	
Veronica americana	American speedwell	
Veronica scutellata	marsh speedwell	
Epilobium watsonii	willow-herb	x (*Epilobium* sp.)
Eleocharis palustris	creeping spikerush	x (*Eleocharis* sp.)
Montia linearis	narrow-leaved montia	
Rorippa obtusa	yellow-cress	
Cardamine oligosperma	bittercress	
Lysimachia terrestris	loostrife	
Spirodela polyrhiza	greater duckweed	

Table C2. Maltby Lake wetland species inventoried by Adolf and Oluna Cěska (ENKON, 2002)

Scientific name	**common name**	Observed by L. Townsend in 2007 (x)
Abies grandis	grand fir	x
Acer macrophyllum	bigleaf maple	x
Agrostis stolonifera	creeping bentgrass	
Agrostis capillaris	colonial bentgrass	
Alnus rubra	red alder	x
Athyrium filix-femina	lady fern	x
Carex obnupta	slough sedge	x
Carex deweyana	Dewey's sedge	
Carex rossii		
Comarum palustre	marsh cinquefoil	x
Cornus nutallii	beaked hazelnut	
Cornus sericea	red osier dogwood	x
Crataegus monogyna	English hawthorn	
Cystopteris fragilis	fragile fern	x
Epilobium ciliatum	hairy willowherb	x
Equisetum arvense	common horsetail	x
Equisetum telmateia	giant horsetail	
Gaultheria shallon	salal	x
Glyceria borealis	northern mannagrass	
Glyceria elata	tall mannagrass	
Iris pseudacorus	yellow iris	
Juncus bolanderi	Bolander's rush	
Juncus effusus	common rush	x
Juncus ensifolius	dagger leaf rush	
Lysichiton americanus	skunk cabbage	x
Nuphar polysepala	yellow pond lily	x
Nymphaea odorata	fragrant water lily	x
Oenanthe sarmentosa	Pacific water parsley	
Phalaris arundinacea	reed canarygrass	
Pteridium aquilinum	bracken fern	x
Populus balsamifera ssp. *trichocarpa*	black cottonwood	
Potamogeton spp.	pondweed	x
Prunus emarginata	bitter cherry	
Pyrola asarifolia	common pink wintergreen	
Pseudotsuga menziesii	Douglas-fir	x
Quercus garryana	Garry oak	x
Rhamnus purshiana	cascara	x
Rosa gymnocarpa	baldhip rose	x
Rosa nutkana	Nootka rose	x
Rubus spectabilis	salmonberry	x

Maltby Lake species cont'd

Scientific name	**common name**	Observed by L. Townsend in 2007 (x)
Salix geyeri	Geyer's willow	x
Salix hookeriana	Hooker's willow	x
Salix lasiandra	Pacific willow	x
Salix scouleriana	Scouler's willow	x
Salix sitchensis	Sitka willow	x
Sambucus racemosa	red elderberry	x
Spiraea douglasii var. *douglasii*	hardhack	x
Taxus brevifolia	Pacific yew	
Thuja plicata	western redcedar	x
Typha latifolia	cattail	x
Urtica lyalii	(?) stinging nettle	
Utricularia gibba	bladderwort	
Utricularia macrorhiza	bladderwort	
Additional Species observed by LT		Notes
Andromeda polifolia	bog rosemary	floating bog along N. shore
Drosera rotundifolia	round leaved sundew	floating bog along N. shore
Kalmia microphylla ssp. occidentalis	western bog laurel	floating bog along N. shore
Ledum groenlandicum	Labrador tea	floating bog along N. shore
Myriophyllum sp.	milfoil	common floating near lakeshore
Rubus ursinus	trailing blackberry	in north wetland
Schoenoplectus lacustris	hardstem bulrush	common along lakeshore
	un-ID tall sedge	along shore by floating bog

Table C3. Prior Lake wetland species observed by L. Townsend (summer 2007)

Scientific Name	Common Name	Notes
Alnus rubra	red alder	
Athyrium filix-femina	lady fern	
Carex sp.	un-ID sedge	(short, slender), may be C. arcta or C. deweyana
Carex obnupta	slough sedge	
Carex sitchensis	sitka sedge	
Cornus stolonifera	red osier dogwood	
Comarum palustre	marsh cinquefoil	near shore
Crystopteris fragilis	fragile fern	
Eleiocharis sp.	spikerush	near shore
Juncus acuminatus	tapered rush	near shore
Juncus ensifolius	dagger leaf rush	near shore
Lysichiton americanum	skunk cabbage	
Mentha arvensis	field mint	
Menyanthes trifoliata	buckbean	near shore
Myriophyllum sp.	water milfoil	
Oenanthe sarmentos	Pacific water parsley	
Potamogeton spp.	pondweed	common along shore
Pyrus fusca	Pacific crabapple	
Rosa nutkana	Nootka rose	
Rubus ursinus	trailing blackberry	
Salix geyeriana	Geyer's willow	
Salix hookeriana	hooker's willow	
Salix sitchensis	Sitka willow	
Salix scouleriana	Scouler's willow	
Sparganium sp.	bur-reed	near shore
Spiraea douglasii var. douglasii	hardhack	
Viola palustris	marsh violet	

Table C.4. Line transect (Swan Lake South), sorted from lakeshore to upland

Latin name	Common name	Total L (m)	% cover	rel. dom.*	1st occurrence (m)	last occurrence (m)	range (m)
Nuphar polysepalum	yellow pond lily	: .: :	: .: :	: .: :	:	:	:
Phalaris arundinacea	reed canary grass	: : :	: : .: :	: : .: :	:	: : :	: : :
Glyceria maxima	giant mannagrass	: .: :	: .: :	: .: :	: .:	: : .:	: : .:
Typha latifolia	cattail	: .: :	: .: :	: .: :	: .: :	:	: .: :
Solanum dulcamara	European bittersweet	: .: :	: .: :	: .: :	: .: :	: : .: :	: : .: :
Salix lucida ssp. lassiandra	Pacific willow	: .: :	: .: :	: .: :	: :	: :	:
Cornus stolonifera	red osier dogwood	: : .: :	: .: :	: .: :	: : .:	: :	: : .:
bare soil & branches		: : .: :	: .: :	: .: :	: :	: : .:	: .:
Salix sitchensis	Sitka willow	: .: :	: .: :	: .: :	: : .:	: : .:	: .:
Salix scouleriana	Scouler's willow	: .: :	: .: :	: .: :	: : .:	: :	: .:
Polyganum sp.	smartweed species	: .: :	: .: :	: .: :	: : .:	: : :	: : :
Rubus discolor	Himalayan blackberry	: .: :	: .: :	: .: :	: : :	: : :	:
Equisetum arvense	common horsetail	: .: :	: .: :	: .: :	: : : .:	: : :	: .:
Total		**: : : .: :**	**: : : .: :**	**: : : .: :**			

Table C.5. Line transect (Swan Lake North), sorted along gradient from lakeshore to upland

Latin name	**Common name**	Total L (m)	% cover	rel. dom.*	1st occurrence (m)	last occurrence (m)	length of range (m)
Nuphar polysepalum	yellow pond lily	0.25	0.09	0.07	0	0.25	0.25
Glyceria sp.	managrass	9.71	3.64	2.63	2	11.7	9.7
Typha latifolia	cattail	9.7	3.63	2.63	3	11.4	8.4
Solanum dulcamara	European bittersweet	9.1	3.41	2.47	5.7	53	47.3
Salix sitchensis	Sitka willow	12.8	4.79	3.47	7	18	11
Salix lucida ssp. lasiandra	Pacific willow	36.6	13.71	9.92	11	77	66
Cornus stolonifera	red osier dogwood	18.9	7.08	5.12	11.5	35	23.5
Spireea douglasii, var. *douglasii*	hardhack	3.8	1.42	1.03	11.7	12.2	0.5
bare ground		18.6	6.97	5.04	12	55	43
Epilobium sp.	willow herb	1	0.37	0.27	24	25	1
Galium sp.	Galium	2.02	0.76	0.55	27.5	178.6	151.1
Phalaris arundinacea	reed canary grass	183.8	68.84	49.84	33.6	261	227.4
Polyganum sp.	smartweed	9.85	3.69	2.67	48.3	82.5	34.2
Brassicaceae	mustard	1.93	0.72	0.52	49.2	81	31.8
Schoenoplectus lacustris	hard stem bulrush	0.24	0.09	0.07	50.2	50.53	0.33
Potentilla anserina	Pacific wilverweed	0.14	0.05	0.04	59.45	60.84	1.39
Eleocharis sp.	spikerush	19.1	7.15	5.18	74.5	84.7	10.2
Gnaphalium sp.	cudweed	0.08	0.03	0.02	79.12	80.3	1.18
Bidens sp.	beggarticks	1.76	0.66	0.48	79.85	85.76	5.91
Asteraceae	dandelion	0.5	0.19	0.14	179	179.5	0.5
Parentucellia viscosa	yellow parentucellia	0.13	0.05	0.04	180.1	180.23	0.13
Dactylis glomerata	orchard grass	9.7	3.63	2.63	243.3	253	9.7
Quercus garryana	Garry oak	9.5	3.56	2.58	248	258	10
Cirsium sp.	thistle	0.6	0.22	0.16	250.6	252.2	1.6
Pseudotsuga menziesii	Douglas-fir	2.5	0.94	0.68	256	259	3
	un-identified grass	6.5	2.43	1.76	260.5	267	6.5
Total		**368.81**	**138.1**	**100.0**			

Start position: edge of emergent vegetation at lake shore, 48° 27' 52.2" 123° 22' 18.6" (+/- 5m)
End position: public trail, 48° 27' 59.2" 123° 22' 11.6" (+/- 5m)
* relative dominance = (%cover species 'x' / total %cover)x100

Table C.6. Wetland vegetation cover, frequency and importance value, in study plots at Maltby L. and Prior L.

Maltby L. (N=16)						
Species	**occ(#)**	**F(%)**	**RF(%)**	**MC(%)**	**RC(%)**	**IV**
Sdo	16	100	12.03	53	32.55	44.58
Lam	16	100	12.03	23	14.13	26.16
Cst	15	93.75	11.28	23	14.13	25.4
Ssi	13	81.25	9.77	20.0	12.28	22.06
Cob	10	62.5	7.52	17	10.44	17.96
Sge	7	43.75	5.26	13	7.98	13.25
Ju	10	62.5	7.52	3.6	2.21	9.73
Afi	9	56.25	6.77	1.6	0.98	7.75
Ca	8	50	6.02	1.8	1.11	7.12
Lin	6	37.5	4.51	3.8	2.33	6.85
Rur	7	43.75	5.26	0.25	0.15	5.42
Ag	4	25	3.01	0.44	0.27	3.28
Sho	3	18.75	2.26	1.1	0.68	2.93
Cfr	3	18.75	2.26	0.06	0.04	2.29
Aru	2	12.5	1.5	1.1	0.68	2.18
Vpa	2	12.5	1.5	0.0013	0	1.5
Paq	1	6.25	0.75	0.063	0.04	0.79
Ep	1	6.25	0.75	0.00063	0	0.75
Total		831.25		162.82		
Prior L. (N=16)						
Species	**occ(#)**	**F(%)**	**RF(%)**	**MC(%)**	**RC(%)**	**IV**
Sdo	11	68.8	13.2	42	32.0	45.27
Lam	14	87.5	13.2	26	19.8	33.06
Ssi	12	75.0	12.4	20	15.3	27.66
Sge	11	68.8	10.7	21	16.0	26.77
Cst	11	68.8	8.3	7.8	6.0	14.22
Ca	14	87.5	5.8	0.6	0.5	6.24
Sho	3	18.8	8.3	6.0	4.6	12.84
Aru	5	31.3	6.6	2.1	1.6	8.21
Afi	9	56.3	7.4	0.47	0.4	7.8
Vpa	7	43.8	5.8	0.0044	0.0	5.79
Mar	9	56.3	5.0	0.32	0.2	5.2
Osa	4	25.0	3.3	0.03	0.0	3.33
Lin	3	18.8	2.5	1.1	0.8	3.32
Pfu	2	12.5	2.5	1.1	0.8	3.32
Cob	2	12.5	1.7	1.0	0.8	2.42
Rnu	2	12.5	1.7	0.60	0.5	2.11
Ssc	1	6.3	0.8	0.94	0.7	1.54
Cfr	1	6.3	0.8	0.00060	0.0	0.83

Abbreviations: occ(#)= no of plots in which sp. occurs; F(%)=frequency, (occ(#)/tot.no.plots)x100; RF = "relative frequency" (F(%)for species(i)/sum of F(%) for all spp.)x100; MC = "mean cover" of all sub-plots sampled; RC(%)= "relative cover" [100x(MC for species(i)/tot. MC for all spp.)]; IV = RF+RC

Table C.7. Wetland vegetation cover, frequency and importance value, in study plots at Swan Lake

Gl	24	60.0	17.1	25.0	20.6	37.78
Par	17	42.5	12.1	26.0	21.5	33.61
Sdu	30	75.0	21.4	2.0	1.7	23.08
Ssi	13	32.5	9.3	11.0	9.1	18.37
Cst	7	17.5	5.0	5.0	4.1	9.13
Sdo	5	12.5	3.6	2.0	1.7	5.22
Ssc	2	5.0	1.4	1.0	0.83	2.25
Ep	2	5.0	1.4	0.08	0.062	1.49
Rdi	1	2.5	0.7	0.025	0.021	0.73
Br	1	2.5	0.7	0.013	0.010	0.72
Sal	1	2.5	0.7	0.000	0.00025	0.71
Po	1	2.5	0.7	0.000	0.00025	0.71
Osa	1	2.5	0.7	0.000	0.00025	0.71
As	1	2.5	0.7	0.000	0.00025	0.71
Total		350		121.11		

Swan L. South (N = 40)						
Species	**occ(#)**	**F(%)**	**RF(%)**	**MC(%)**	**RC(%)**	**IV**
Cst	38	95.0	18.1	51	48.01	66.11
Ssi	20	50.0	9.52	20	18.83	28.35
Sdu	38	95.0	18.1	3	2.82	20.92
Par	27	67.5	12.86	8.2	7.72	20.58
Slu	16	40.0	7.62	8.1	7.63	15.24
Ag	9	22.5	4.29	4.8	4.52	8.8
Sge	9	22.5	4.29	4.2	3.95	8.24
Sdo	11	27.5	5.24	2.5	2.35	7.59
Ep	13	32.5	6.19	0.08	0.07	6.26
Ssc	5	12.5	2.38	3.3	3.11	5.49
Osa	8	20.0	3.81	0.027	0.03	3.83
Sho	2	5.0	0.95	0.70	0.66	1.61
Gl	3	7.5	1.43	0.00080	0	1.43
Ga	3	7.5	1.43	0.00080	0	1.43
Tla	2	5.0	0.95	0.15	0.14	1.09
Bi	2	5.0	0.95	0.013	0.01	0.96
Sla	2	5.0	0.95	0.0050	0	0.96
Sba	1	2.5	0.48	0.15	0.14	0.62
Sp	1	2.5	0.48	0.00030	0	0.48
Total		525.0		106.22		

Appendix D - Summary of Willow/Reed Canarygrass Pilot Project

Introduction

As shown in Chapter 4, Reed canary grass (*Phalaris arundinacea*) (RCG) dominates a large area (14 ha) of wetlands at Swan Lake. Paleoecology in the form of a pollen study (Appendix A) established that grass was not a significant component of the pre-disturbance wetland vegetation community, while willow (*Salix* spp.) was one of the dominant species. Thus a restoration program to control RCG and restore native willow is justified.

RCG is an aggressive species that out-competes most native wetland species, particularly in disturbed environments with widely fluctuating water levels and high nutrients and sediment loads (Kercher and Zedler, 2004). However, it is intolerant of shade, thus a planting regime that establishes a canopy rapidly enough to create dense shade may be an effective control method where shrubs and trees are a desirable replacement (Kim *et al.*, 2006). Willow is widely used for bioengineering, phytoremediation, as an energy crop for biomass, and is traditionally used by Native Americans for basketry, while locally First Nations used it for making fish nets of various types, especially the reef-net (Kuzovkina and Quigley, 2005; Anderson, 1999; Lake, 2007; Turner, 1998). The reef-net is a key practice in the culture of the WSÁNEC people, who are indigenous to Saanich and Swan Lake watershed (Claxton, 2003). Researchers in California have demonstrated that pruning or burning has beneficial effects on willow regrowth and community structure, by creating a mosaic of various life-stages (Anderson, 1999; Lake, 2007). This effect could also be depicted as increasing ecological resilience (Holling, 2001).

The objective of this project was to, 1) evaluate the control of RCG and the establishment of a stand of native willows, using a mulching and live staking technique based in part on a study by Kim *et al.* (2006); and 2) to advance knowledge about cultural use of willow and establish a source of materials for constructing reef nets, based on a collaboration with Nick Claxton (University of Victoria PhD candidate and member of the WSÁNEC

First Nation).

Methods

Three (approximately 100m^2) plots at Swan Lake Nature Sanctuary were mulched and planted; Sites A and B1 in early 2007, and Site B2 in early 2008. All sites consisted of dense RCG monotype prior to site preparation. Mulching was effected with a single layer of cardboard, laid over compacted (or cut/scraped) grass, with approximately 5-10 cm of leaf mulch placed on top. Willow cuttings were sourced from nearby areas and consisted of *S. sitchensis, S. scouleriana S. lucida,* ssp. *lasiandra,* and *S. hookeriana*; 1-m long live cuttings were pushed through the mulch into the soil to about half to three quarters of the length of the cuttings at a 60cm spacing. Volunteers were recruited from St. Michael's University School, the University of Victoria, the local neighbourhood, and (in the 2008 planting) from the Saanich (Tsawout) First Nation with Nick Claxton's assistance.

In order to assess the shading effect of the willow, photosynthetically active radiation (PAR) was measured, under the willow plantings using point and line sensors (Comeau, 2000; Lieffers *et al.*, 1999; Fielder and Comeau, 2000; Fielder, pers. comm.). Only Site A was thus measured, since the other site was subject to some shade from adjacent trees. Species composition, cover and average height of willow shoots was recorded several times throughout the two years, and documented with photopoint monitoring (Hall, 2001). A few samples from plots A and B1 were destructively sampled to calculate the woody biomass (in oven-dried weight) for some indication of stand productivity; RCG under the willow canopy was also weighed and compared with open-grown samples randomly selected from nearby the sites. Biomass drying was carried out at the Pacific Forestry Centre in ovens designed for the purpose, with the aid of Ann Harris, a soils researcher at the centre. Biomass data were also used to calculate carbon sequestration, to assess the potential of the method for climate change mitigation that could enhance the viability of the strategy (e.g. by obtaining funding under this objective).

Results

The planted willow in sites A and B1 sprouted very quickly in the spring after the stakes were planted, with a very low (<1%) rate of unsuccessful plantings. Growth over the summer was vigorous, and by the end of the summer a dense thicket had established, with an average shoot height of approximately 1-2 m. The later (2008) planting at Site B2 also appeared to be establishing quite well at the end of one season, with the average height of the planted willows between 1 and 1.5 m.

At Site A, after one season of growth, the willows intercepted 90% of PAR received at the site, compared to a short time after planting; this increased only slightly to 91% light interception by August 2008. A one-way ANOVA (p=0.05, F=4.34) and a Tukey Test supported the conclusions of significant difference between the two under-canopy readings and the initial pre-planting reading, and no significant difference between the two (2007 and 2008) under-canopy readings.

In September, 2008, biomass measurements indicated a 99.3% reduction in above-ground biomass of RCG at Site B1, and 93.4% reduction at Site A. A one-way ANOVA with Tukey Test supported the conclusion that there are significant differences between all three samples (two willow plots and open grass).

Biomass sampling of woody growth and leaves (and conversion of biomass to carbon) yielded an estimate of carbon sequestration of 453 $gC/m^2/y$ and 1098 $gC/m^2/y$ (or 4.53 tC/ha/y and 10.98 tC/ha/y), for Sites B1 and A, respectively. I also calculated carbon sequestration according to empirical formulae in Grelle *et al.* (2007), based on only the woody biomass of shoot growth, which gave an estimate of 3.43 tC/ha/y and 8.68 tC/ha/y for sites A and B1 respectively.

The biomass of RCG collected from the open fields was estimated to represent an instantaneous storage value of 1645 gC/m^2, however estimating sequestration is complicated by annual die-off of the grass, and high rates of decomposition (Jelinski, 2007). Jelinski (2007) estimated a sequestration rate of approximately 0.93 tC/ha/y for RCG in a Wisconsin wetland.

Although the sample size was small, a *post-priori* power analysis confirmed power well in excess of 99% ($\alpha = 0.05$) for both the biomass and the light measurements, supporting the conclusion that real differences were detected. Limitations of the analysis were a small sample size, large variances and non-random sampling (the latter in order to best characterize the conditions in the interior of the small plots, as opposed to random sampling that would be more subject to edge effects).

Discussion

RCG is an invasive species that reduces wetland vegetation biodiversity, among other effects (Zedler and Kercher, 2004; Perkins and Wilson, 2005), yet few control methods have been successful (Lavergne and Molofsky, 2006).

The technique applied in this project was successful in re-establishing a native willow stand and displacing the invasive RCG, at least in the short term, as shown by the large reduction in grass biomass (93% and 99%) under the willow canopy compared to an adjacent open area, as well as qualitative observations. A willow canopy was established within one growing season that intercepted 90% of photosynthetically active radiation; this shade effect is thought to be the main mechanism for suppression (Kim *et al.*, 2006).

Sheet mulching with various materials, including cardboard, is a technique commonly used in the practice of “Permaculture” (Holmgren, 2002; Agroforestry Net, Inc., 2008), however it is apparently not widely used in ecological restoration. Some advantages of this technique include its effectiveness in suppressing underlying vegetation (at least temporarily), the fact that it does not physically disturb soil structure, and the beneficial use of a “waste” product.

Biomass calculations show that willow plantings using this technique grow rapidly, representing a possible carbon sequestration strategy as well as the potential for phytoremediation, i.e. improvement of lake inflow water quality through uptake of nutrients and pollutants. First Nations cultural use of harvested material is another possibility that has been established at this site. Multiple benefits such as these are important to establish incentives for scaling up the technique in a budget-limited context.

The second phase of planting, at site B2 in 2008, involved First Nations participants from the Tsawout band, as well as ethnoecology students from the University of Victoria. An agreement was reached with the Swan Lake Christmas Hill Nature Sanctuary, allowing members of the Tsawout Nation to harvest willow from one of the sites (Site B2) in the future, for making a scale model (and, later, a full-scale version) of a traditional reef-net, objectives related to N. Claxton's PhD thesis for revitalising this traditional knowledge. Thus this collaboration enabled mutual learning by the diverse participants, of wetland ecology and First Nations culture.

Conclusions

This study suggests that the mulching/planting technique tested is a successful method for replacing invasive RCG with native willow at Swan Lake Nature Sanctuary and similar local wetland areas. This justifies larger scale applications of the technique, ideally with quantitative monitoring to better evaluate the results. The project also established a link between the nature sanctuary and a local First Nations community, with the potential to foster long-term collaboration and contribute to revitalisation of traditional ecological knowledge.

Appendix E - Swan L. Sediment Data

Table E1. Sediment data from Swan Lake, collected in 2002 at various depths, compared to guidelines for aquatic life and other lakes

Information	Swan L. sediment (mean) n=5	Swan Lake st. dev.	BC Lakes Mean	BC Lakes st. dev.	Beaver L. sediment data	Interim Sed. Qual. GL for Aquatic Life	Sed. Qual. Obj. (TEC)[1]	Sed. Qual. Obj. (PEC)[2]
Source	Kenny, 2003	Kenny, 2004	Rieberger, 1992	Rieberger, 1992	Rieberger, 1992	CCME, 2002	Wisconsin Dept. Nat. Res. 2003	Wisconsin Dept. Nat. Res. 2003
Parameter								
tot. inorg. C	**1700**	800	3360	2170				
tot. org. C	**149000**	72664	166500	74970				
total C	**149200**	72410	169800	74080				
total N	**7900**	3574	11610	5980	1710			
avail N (NO2+NO3)								
total P	**1704**	174						
Al	**26660**	6204	19730	10530	9380			
Sb	**1.7**	0.3						
As	**7.5**	0.8	44.92	151.60	24.00	5.9	9.8	33
Ba	**186**	46	79.17	54.25	33.00			
Be	**0.4**	0.1	1.00	0.00	1.00			
Bi	**0.3**	0.1						
Cd	**1.53**	0.25	1.16	0.86	1.00	0.6	0.99	5
Ca	**14960**	2907	6750	2480	5400			
Cr	**50.9**	9.6	360.00	331.30	300.00	3.73	43	110
Co	**14.9**	1.6			10.00			
Cu	**114**	10	612.30	504.50	300.00	35.7	32	150
Fe	**40920**	7457	306900	288000	119000		20000	40000
Pb	**223**	91	39.35	42.17	25.00		36	130
Mg	**9818**	950	49000	77870	33000			
Mn	**661**	59	2307	7807	281.00		460	1100
Mo	**3.6**	0.5	7.67	7.49	7.00			
Ni	**42.2**	5.1	22.73	11.51	16.00		23	49
K	**948**	168						
Se	**1**	0	13.89	7.53	10.00			
Ag	**1**	0					1.6	2.2
Na	**803**	122						
Sr	**73.6**	10.0						
Te								
Tl	**0.18**	0.04						
Sn	**4.5**	0.8	10.08	15.24	8.00			
Ti	**657**	142	365.10	245.50	582.00			
V	**70**	9	55.54	27.03	59.00			
Zn	**401**	38	70.57	32.01	57.00	123	120	460
Zr	**2.9**	0.6						

Notes:

1. TEC = threshold effects concentration

2. PEC = probable effects concentration

Appendix F - Questions for Systems Models of Swan Lake Watershed Ecosystem Components

(based on Bennett *et al.,* 2005)

		Lakes	Streams	Wetland (S.L.)	Uplands
Assmt and Problem Dfn	What aspect of the system should be resilient?	Water quality	Biophysical conditions, water quality	Native vegetation community	Vegetation cover and ET
	What kind(s) of change would we like the system to be resilient to?	Agriculture, urban development	High flow events; development in watershed	Invasive species	Development and human pop. growth
Feedback Processes	What variables are changing?	algae; P in water[1]	flow regime (+flashy); channel form and veg.	Mostly unchanged over past 30 y	Vegetation cover
	What processes and drivers are producing these changes?	Incr. P loading from agriculture and urban runoff	Incr. EIA; direct channel alterations	Previous clearing and disturbance	Urban development and agriculture
	What forces control the processes that are generating change?	Land use planning & mgmt; P recycling in lake	Land use planning & mgmt	Aggressive characteristics of grass; (possibly) control of groundwater	Human population; cheap fossil fuels
Systems Model Design	What are the key elements and how are they connected?	See Fig. A	See Fig. B	See Fig. C	See Fig. 6.1
	What positive and negative feedback loops exist in the model and which variables do they connect?	+algae (P avail from loading/ recycling); -algae (P lt'd from flushing/ grazing)	+degraded (incr. runoff, loss of veg), -healthy (less surf. runoff, intact veg/ soils)	+grass-dominated; -shrub-dominated	+urban barrens; -native plant dominated
	What, if any, are the intervening factors that influence or control these feedback loops?	nutrient loading from urbanization	urbanization	urbanization	human population; building practices and technology
	What (if anything) moves the system from being controlled by one feedback loop to another?	O2 content of water; level of P loading	increase in EIA, decrease in water quality	clearing and disturbance; ongoing fluct. in water levels, sediment, nutrients	Patterns of land development req'ing large-scale clearing and minimal replanting
Identifying Resilience Surrogates	As indicated by the feedback loops, what is the threshold value of the state variable?	P conc. when P recycling becomes signif.	amount of EIA when degraded cond's become significant	Amount of shrub clearing before grass dominates	Amt. of disturbance that causes significant ecol. degradation
	How far is the state variable from the threshold value?	est. to be far exceeded	varies by stream/reach (see PFC assmt)	est. to be far exceeded	est. to be far exceeded
	How fast is the state variable moving toward or away from the threshold?	away (on turbid side) at slow to moderate rate	away (on degraded side) at slow rate due to cohesive soils	may be static or slowly moving back toward threshold	est. to be moving moderately fast toward further degradation
	How do outside shocks/controls affect the state variable and how likely are those shocks/controls?	More extreme rainfall events could incr. loading	climate change may cause more extreme runoff events; increased urban devel. likely	sediment & nutrient loading favour grass dominated state	economic crisis, peak oil, climate chg may all worsen effects
	How are slow variables changing in ways that affect the threshold location?	Accumulation of P in watershed soils may be occurring	development density in watershed is increasing	Gradual shifts in spp. composition (both native and non-native)	Species extirpation may speed shift to 'urban barrens'
	What factors control changing of these slow variables?	Ag. practices, residential landscaping, EIA	municipal planning; prov. regulations req'ing buffers	Seed/ propagule source from outside areas; restoration interventions	Habitat fragmentation; soil disturbance; pollution
Additional Q's (by L. Townsend)	What is current state of the system?	Algae-dominated	Degraded (non-functional and poor water qual)	grass-dominated	urban barrens
	Is current state desired or undesired?	undesired	undesired	undesired	undesired
	What is estimated stage or point in the adaptive renewal cycle?	K	K	r to K	K

Appendix G - Five Processes Details and Assessment of Swan Lake Watershed

The following is a summary of the five processes used as categories of criteria for assessing ecological health of an urban watershed, based on traditional Chinese philosophy and western science, as discussed in Chapter 6. Examples of processes and inferences are given for Swan Lake watershed, and the criteria (listed in Chapter 6) are evaluated for Swan Lake watershed in Table G2.

Water is fundamental to life on earth. Acknowledging this importance, in Chinese philosophy water is often seen as the foundation for all the other processes (Maciocia, 1997). It is a primary reactant in photosynthesis, which in turn forms the basis for the world's food webs. Water is cycled through the watershed via a number of pathways, and performs critical functions in ecosystems, by linking terrestrial, aquatic and riparian ecosystems, acting as a chemical solvent, and dissipating energy through cyclical processes, including evaporation/condensation, respiration/photosynthesis, and chemical precipitation/dissolution; thus it is the "bloodstream of the biosphere" (Ripl, 2003). The role of water is intertwined with the functions of vegetation, which helps to circulate water via the "green water cycle," as discussed previously. Whereas natural ecosystems tend to favour short-circuited water cycles and a large proportion of water partitioned to the "green" portion of the cycle, urban water management is focused on drainage and flood conveyance, whereby surface runoff increases dramatically at the expense of other pathways. Chapter 2, illustrated how stream channelization and wetland drainage began in the 1850s, and continued to modern times with land clearing and development. There has been some improvement of this management regime, e.g. in the form of wetland restoration pilot projects (e.g. Malmkvist, 2002), and a municipal bylaw that requires on-site stormwater management for new developments when downstream infrastructure is not able to convey increased flows (District of Saanich, no date). However, on a watershed scale impervious surfaces constitute one of the dominant land cover types at ~25% (Chapter 4), and there are few "low impact development" stormwater management facilities. I estimated that lost 'green water' (vapour) flows have resulted in a major shift in the energy flux in the watershed, as discussed in Chapter 6, potentially adding to the urban heat island effect and reducing human and ecosystem adaptability to anticipated warmer temperatures with climate change. The flow patterns in the streams assessed in this study have also been significantly altered from pre-disturbance conditions, as discussed in Chapter 5, and today are typical of urbanised systems. These patterns reduce the ability of the stream channels to function properly, and to provide associated habitat and human values. Water quality is also an important attribute of this category, and as discussed in Chapter 5 and above, is degraded in Swan Lake watershed.

Vegetation is represented as "wood" in the Chinese system, is interpreted here to refer to all types of vegetation. Vegetation provides "fuel" for metabolism by consumers (a "fire" process as described below), and helps to dissipate solar energy and moderate temperature extremes (Schneider and Kay, 1994; Luvall and Holbo, 1989). Vegetation is also critical for taking up carbon dioxide and replenishing oxygen in the atmosphere, providing the conditions for the vast majority of organisms on Earth. Plants provide habitat, protect and retain soil, and influence water and energy cycles, as noted above (US EPA, 2002). Vegetation was assessed at the scale of Swan Lake Nature Sanctuary, and at the watershed scale in Chapter 4. At the site scale, invasive species are a major concern, and limit the ecosystem services provided by the site; in particular, reed canarygrass limits biodiversity, evapotranspiration and carbon sequestration that could be better effected by native woody vegetation, which as discussed in Chapter 2 was the dominant pre-agricultural vegetation type. At the watershed scale, most of the pre-existing native vegetation has been cleared, although the "urban forest" provides a number of important services.

Energy is an interpretation of the Chinese five-processes element "fire." Solar energy provides the basic fuel for life, which is transformed by green plants into chemical energy through photosynthesis. In healthy ecosystems, well-developed structures and functions help to efficiently dissipate this energy in networks of production/consumption/decomposition (Odum, 1969; Ripl, 2003). Disturbances are another form of energy that, in an appropriate frequency and magnitude, help to maintain ecosystem function (Pickett and White, 1985). When excess energy becomes bound in biomass or other internal structures, a disturbance occurs that releases some energy to allow the ecosystem to persist (or to change to an alternative stable state); in effect, the adaptive renewal cycle (Holling, 1992; Gunderson and Holling, 2002), is *an energy-dissipation system*. Human management can mimic these disturbances, such as First Nations management of willow shrubs (Appendix D). In urban systems, previously “closed” and cyclical energy processes are typically transformed to “open”and one-way processes, where 'waste' products are generated and exported to other areas, and pulse disturbances are replaced with ongoing “press disturbances.” For example, erosion of agricultural land causes nutrient mobilisation into waterways, a likely contributor to eutrophication in Swan Lake, and depleted soil fertility is replaced with imported fertilisers; this not only exacerbates the local problems, but creates other problems such as carbon emissions associated with fertiliser production and transportation (Odum, 2007).

Soil (“earth” in the Chinese system), also potentially including sediment, consists of a combination of mineral matter, organic matter and organisms that support terrestrial, riparian and benthic ecosystems. Physical, chemical and biological processes are important to maintaining soil health and productivity, to ensure provision of ecosystem services, such as nutrient cycling, decomposition, and plant health (Bunning and Jiménez, 2003). Soil biota include a vast array of poorly understood organisms including bacteria, archaea, invertebrates, fungi and micorrhizae (Bunning and Jiménez, 2003; van der Heijdel *et al.*, 1998). Soil is influenced by disturbances (energy) such as land clearing, ploughing, fire and flooding/erosion. Loss of soil (and soil/nutrient pollution of aquatic environments) due to land clearing and inappropriate soil management is a problem of global scale associated with human activities (Ripl and Hildmann, 2000). In general, biological and abiotic processes in soils create a living matrix that supports healthy plants and allows infiltration and sub-surface flows of water. Vegetation in turn protects soils from erosion with root masses and protective cover. In urban systems, soils are typically exposed, eroded, compacted and sealed by impervious surfaces. This serves to disconnect and fragment terrestrial and aquatic habitats, and can make re-establishment of native (and/or desired) vegetation challenging. By shedding water, urban surfaces also prevent water retention that otherwise supports plant growth and climate cooling. Soil was not directly assessed in this study, however these processes are discussed in general terms related to land use.

Nutrients and (inorganic) elements are an interpretation of the Chinese process classified as "metal." Nutrients/elements such as nitrogen, phosphorus, salts and metals influence plant health, and are produced by weathering of geologic materials as well as from mineralisation of complex molecules by micro-organisms. In healthy watersheds, nutrients are released gradually and in periodic pulses (e.g. due to forest fires) in a pattern that supports plant productivity. As discussed in Chapter 2 and 5, excessive nutrient loading to Swan Lake occurred in the past and is on-going today. These nutrients are being lost from the land (depleting soil fertility) and are negatively affecting aquatic ecosystems (e.g. with algal blooms and depleted dissolved oxygen). Heavy metals concentrations are also a concern, due to water pollution. Inorganic elements can also be considered as geologic and mineral deposits, the results of weathering and other processes. In the Chinese systems, water is "generated" from metal; similarly, groundwater is stored in and discharged from mineral aquifers.

Table F1 provides some examples of how the five processes influence one another, and Table F2 summarises how Swan Lake watershed might rate against the criteria described in Chapter 6 (note this is an example, not meant to represent a full assessment, which would require an interdisciplinary team and more information).

Table F.1 Matrix of interactions between five (ecological) processes

Process Affecting	Process Affected	Description
Energy	Water	Solar energy evaporates water, absorbing heat from surroundings
		Excessive evaporation/solar energy dessicates landscape
	Vegetation	Solar radiation drives photosynthesis, plant growth
		Excessive radiation/disturbance damages vegetation
	Soil	Heat (solar/biochemical) accelerates microbial decomposition
		Physical disturbance (trampling, excavation) disrupts soil structure
	Inorganic Elements	Fire releases bound nutrients and elements
		Excessive freshwater nutrient loading leads to reducing conditions in sediment, frees soluble iron(II), recycles P
		Excessive disturbance accelerates nutrient loss
Soil	Water	Soil structure (e.g. topography, stream channel form) slows flows of water
		Exposed, eroded soil can “pollute” water with sediment
	Vegetation	Provides structure and chemical nutrients for plant growth
		Excess sedimentation can prevent vegetation establishment
	Energy	Microbial decomposition provides nutrient (energy) source for plants
		Mobilisation of soils over-enriches water bodies; soil loss depletes soil fertility
	Inorganic Elements	Microbes effect mineralisation of complex molecules
Inorganic Elements	Water	Water is stored/released from groundwater; mineral content supports biota
		N, P contribute to aquatic ecosystem productivity
		Excessive nutrients lead to algae blooms, eutrophication
	Vegetation	Plants require macro and micro-nutrients for growth/health
		Excessive nutrients and certain elements toxic to plants
	Energy	Nutrients and elements provide basis for chemical energy through primary production
		Excessive nutrients can over-accumulate and lead to ecosystem shifts (e.g. eutrophication, fuel build-up in forests)
	Soil	Weathering contributes to soil composition/structure
Water	Vegetation	Water used for photosynthesis, transpired for cooling
		Excessive/insufficient water causes plant mortality
	Energy	Evapotranspiration transforms solar radiation to latent heat; cools atmosphere
		Excessive water (flooding) can limit productivity/metabolism
	Soil	Water infiltrates and is stored in soil, supporting biological processes
		Excessive water flows erodes soil
	Inorganic Elements	Water dilutes nutrients, dissolves salts
		Water mobilises nutrients/minerals with weathering of rock, erosion of soils
Vegetation	Water	Plants contribute to short-circuited water cycles (condensation/evaporation), aid in water storage/infiltration in soil
	Energy	Plants transform solar energy to chemical energy; provide basis for food chain.
		Evapotranspiration by plants cools the atmosphere, redistributes solar energy in the landscape.
	Soil	Vegetation protects soil with shade, litter; holds soil in place with roots
		Uncontrolled growth can deplete soil nutrients
	Inorganic Elements	Vegetation returns nutrients to soil via decomposition.
		Excessive growth/harvesting can deplete soil nutrients

Table F.2. Preliminary evaluation of Swan Lake watershed using five-processes assessment (see Chapter 6 for criteria forming the questions)

Q.#	Possible "answers" and Notes in response to Ecological Health Criteria
١	No. Most of the watershed (i.e. residential and agricultural areas) is irrigated (much with drinking water); little anecdotal evidence of landscaping with native plants or crops tolerant to local rainfall patterns; conservation practices only implemented during drought.
٢	No. PFC assessment (Chapter 3) revealed most stream channels assessed were non-functional or functional-at-risk. Many wetlands drained/filled in.
٣	Not assessed, but suspected to be No. Watershed is 25% impervious; few stormwater retention systems; native forest largely cleared replaced w. grass/crops.
٤	No. Several water quality indices exceed guidelines for aquatic life (Chapter ٥).
٥	Unknown but suspected to be Yes with qualifications. Remnant natural areas and street trees, residential areas appear diverse. However vegetation may dominated by non-native species, much with limited habitat value.
٦	Unknown. Likely Yes in some areas but No overall. Agricultural areas likely No. Urban forest assessment needed.
٧	Unknown but suspected to be No. Most vegetated areas (residences and agriculture) depend on irrigation; floodplains are cultivated with dry-land species (Blenkinsop Valley)
٨	Unknown. Urban forest assessment needed.
٩	No. Invasive species are a problem in practically all natural areas (Chapter 4; Saanich Environmental Services, pers. comm.)
١٠	Unconfirmed but suspected No (e.g. Chapters 4, 5) due to land clearing and impervious surfaces. Micrometeorological studies needed.
١١	No. Natural areas lack disturbance (e.g. fire, forest litter management, pruning); hydroperiod and hydrological regime altered (Chapter 5). More detailed ecosystem studies and long-term monitoring required.
١٢	Unknown but suspected to be No. Nutrient levels excessive (lake system has already shifted to eutrophic); also could be a concern to marine (estuarine) system. Fertilisers use is likely high (e.g. turf farm, golf courses). Further energy quantification needed.
١٣	Not quantified but likely No. Ongoing ("press") disturbance (soil erosion, annual cultivation in floodplains); flashy hydrograph erodes stream channels
١٤	No. Storm drain network transfers disturbances (e.g. pollution) to aquatic areas; few wildlife corridors (except Lochside Trail).
١٥	No. Stream channels eroded; water quality monitoring indicates high turbidity (Chapters ٥ ,٣).
١٦	Not quantified but likely No. Most historic vegetation cleared or substantially altered (Chapters 4, 6); streams lack large wood; coarse wood not usually part of landscaping practices.
١٧	Unknown but suspected to be No due to large-scale disturbance (impervious surfaces, annual cultivation practices, construction site practices). Soil studies needed.
١٨	Unknown but suspected to be No due to large-scale disturbance (impervious surfaces, annual cultivation practices, construction site practices). Soil studies needed.
١٩	No. Eutrophication is evident in Swan Lake (Chapter 5); fertiliser use in agriculture and residential areas unknown but suspected to be high.
٢٠	No. Nutrient runoff is occurring (Chapter 5). All human waste is exported (to ocean disposal). Imports (food, fertiliser) likely high. Composting practices unknown. Nutrient/energy budget calculations needed to quantify.
٢١	Unknown but likely No. Habitat unable to support higher predators and consumers (but some present at Swan Lake). Most of human consumption relies on outside production.
٢٢	No; metals in water exceed guidelines (Chapter 5). But biological effects unknown. B-IBI studies recommended. Water quality and soils testing could also help ID and mitigate pollution hot-spots.