ELSEVIER

Journal of Hazardous Materials 61 (1998) 163–173

JOURNAL OF HAZARDOUS MATERIALS

Urban watershed ecological risk assessment using GIS: a case study of the Brunette River watershed in British Columbia, Canada

Paul A. Zandbergen *

Institute for Resources and Environment, University of British Columbia, 2206 East Mall, Vancouver, BC V6T 1Z3, Canada

Abstract

Urbanization has a dramatic impact on the health of local streams. The complexity of the many stressors, pathways and ecosystem functions at risk presents a serious challenge to traditional scientific and management approaches. To overcome this complexity, this study developed a general framework and specific procedures for a screening level ecological risk assessment for urban watersheds, and applied it to the case of the Brunette River watershed, a small urban watershed of 70 km^2 in the Vancouver area of British Columbia, Canada. A generic conceptual model was developed and a set of key indicators was selected: impervious areas, riparian habitat, pollutant loadings, water quality, sediment quality, fish health and public health. Information on each of the indicators was transformed into a single dimensionless score. Two indicators (impervious areas and water quality) were selected for a more detailed evaluation of spatial and temporal patterns using a Geographic Information System. Results were displayed in hypermedia modules and presented to local watershed professionals and decision-makers as part of the ongoing development of the methodology. The integrated approach, using a limited set of key indicators and GIS maps to visualize complex scientific information, was well received as a decision support tool. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Watershed management; Urban watershed assessment; Geographic information system; Ecological risk assessment; Impervious areas; Water quality index

1. Introduction

Urbanization of a watershed poses significant risk to aquatic ecosystem health. These risks result form a variety of stressors, including physical (removal of vegetative cover,

---

* E-mail: pzand@unixg.ubc.ca

PII S0304-3894(98)00120-4

creation of impervious areas, in-stream modifications), chemical (discharges from industrial operations, atmospheric deposition, diffuse non-point sources from various landuses, accidents and spills) and biological (pathogens from human and animal waste, introduced species).

The complexity of the system makes it difficult for traditional scientific approaches to come up with simple answers. Local managers and decision-makers, however, have to balance many other non-scientific concerns, and an elaborate discussion of the scientific complexities is not possible in most decision-making processes. It is argued here that an integrative approach is required, balancing the complexity of the scientific analysis with the expressed need by management for simple and clear answers on the state of the watershed and the types of management actions required to achieve certain objectives. To facilitate this integrative approach a methodology was developed for the screening level ecological risk assessment of urban watersheds. The Brunette River watershed was used as a case study to test the usefulness of this methodology: extensive data on the watershed was assembled and analysed, and the results presented to local stakeholders.

2. Development of an assessment methodology

2.1. Ecological risk assessment

Ecological risk assessment presents a useful framework to organize complex scientific information into a form which is meaningful to management, but has not been

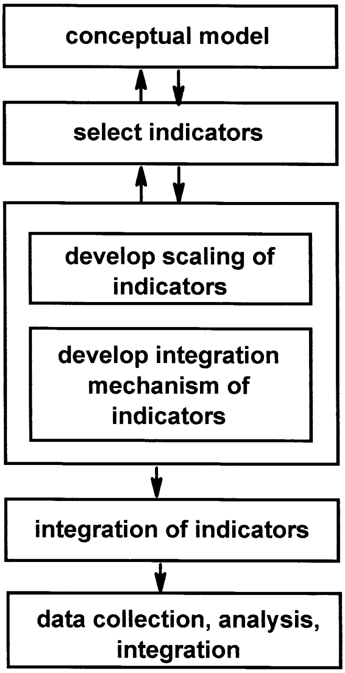

Fig. 1. Procedure for screening level ecological risk assessment used in this study.

applied widely to urban watersheds. The general framework for ecological risk assessment used here closely follows the framework suggested by the US Environmental Protection Agency [1]. The methodology developed here is intended to serve as a screening level assessment, which helps to identify areas of concern and guide the directions of more detailed studies.

Fig. 1 outlines the specific procedure developed in this study for a screening level ecological risk assessment of urban watersheds. The procedure is analogous to the use of set of risk indices to classify watersheds and other regions, such as demonstrated in forested watersheds in British Columbia [2] and groundwater in the Netherlands [3].

2.2. Conceptual model and indicator selection

A generic conceptual model was developed to describe the relationships between various elements of the urban watershed ecosystem and their interaction with human activities (Fig. 2). An extensive list of potential indicators (Table 1) was identified which can be used to describe in more detail the generic relationships identified in the figure. The conceptual model and the list of indicators are based on an extensive literature review [4–8] and the input from a group of experts on watershed assessment [9]. The generic conceptual model and the list of indicators serve as a starting point for the development of a more specific model for a particular watershed.

Since the objective was to develop a simple yet fairly comprehensive screening level assessment, a small set of key indicators was selected based on the criteria in Table 2, which were used successfully by the Centre for Watershed Protection [4] to assess stormwater control programs and practices. Fig. 2 places these indicators in the generic

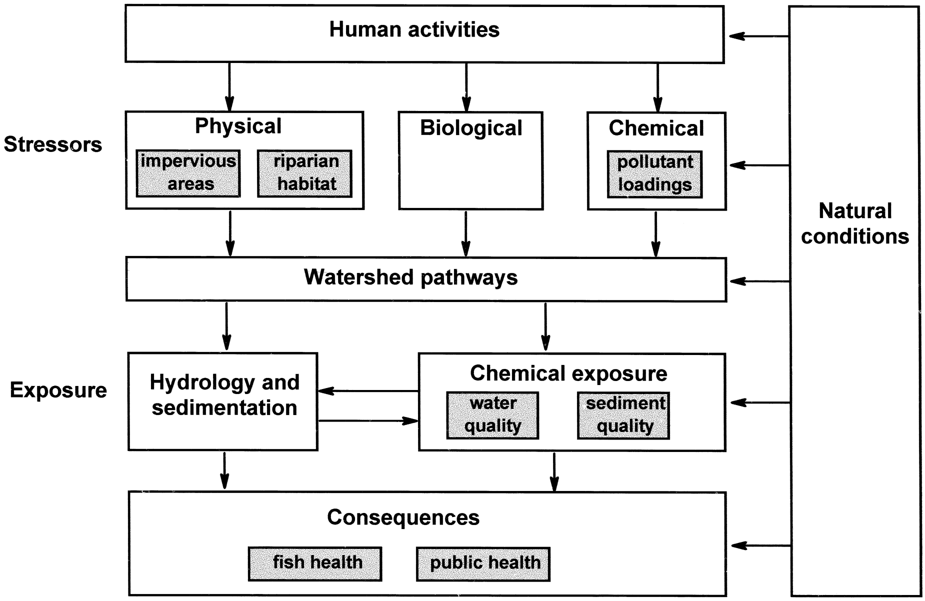

Fig. 2. Generic conceptual model for urban watersheds and selected indicators.

Table 1
Set of potential indicators in urban watershed assessment

Category	Indicators
Natural conditions	soil types / surficial geology
	climate / topography
Human activities	commercial / residential landuse
	industrial activities
	construction / public utilities
	vehicle use / roads and rail
	dangerous goods movement
	long-range transport of air pollutants
Physical stressors	impervious areas
	riparian habitat
	stream crossings
	water withdrawal
	in-stream work
	channel modifications
Biological stressors	introduced species
	pathogens
Chemical stressors	atmospheric deposition
	spills and leaks
	point sources
	organic material and animal wastes
	fertilizer and pesticides
	stormwater runoff
Watershed pathways	stormwater drainage system
	infiltration / leaching
Physical exposure	stream hydrology
	erosion and sedimentation
Chemical exposure	water / groundwater quality
	sediment quality
	toxicity bioassays
Consequences	fish habitat / organism health
	recreation / public health

conceptual model and Table 3 gives a short description of each. Two indicators, impervious areas and water quality were selected for a more detailed evaluation as test cases for the procedure.

Table 2
Criteria for the use of indicators in watershed assessment

Geographic range: multiple geographic regions
Baseline control: establishment of baseline conditions
Reliable: wide range of applications
Accuracy: identification of the health or quality of the aquatic system
Low cost: cost effectiveness
Repeatable: varying environmental and geographic conditions over a long period of time
Scale: site, sub-watershed, watershed and river basin scale
Acceptance and familiarity to watershed professionals and members of community groups
Inexpensive, rapid and relatively easy personnel training

Table 3
Description of the key indicators used in screening level assessment

Indicator	Description
Impervious areas	impervious areas created by roads and buildings, as a percentage of the total area
Riparian habitat	quality and extent of the vegetative cover in a 30 m buffer zone around streams
Pollutant loadings	loadings of various organic and inorganic pollutants into the aquatic system, both continuous and incidental, point and non-point
Water quality	water quality conditions, expressed in a Water Quality Index
Sediment quality	sediment quality conditions, expressed in a Sediment Quality Index
Public health	threats to public health, based on the human uses of the watershed: drinking water (where applicable) and recreation
Fish health	fish health as measured by total fish populations, population composition, and contaminants in fish

2.3. Scaling of indicators

In the screening level assessment, information on the indicators is integrated and transformed into a dimensionless score from 0 to 100, with 100 representing no risk or perfect watershed health and 0 representing extremely high risk or extremely low watershed health. Five ranges were chosen within this scale, based on a qualitative description of the health of the ecosystem: from 0 to 25 (very poor), 25 to 50 (poor), 50 to 70 (fair), 70 to 90 (good), and 90 to 100 (excellent). This scaling process is different for each indicator. In some cases a large number of parameters has to be integrated into a single measurement; in others one parameter is sufficient. For all indicators a scaling curve, formula or table has to be developed for the transformation into a dimensionless score; the qualitative descriptors for the five ranges serve as a guide for this transformation. The scaling process for impervious areas and water quality is described below; detailed descriptions for the other indicators can be found in Ref. [10].

2.4. Impervious areas

Urbanization of a watershed can result in significant impacts on stream health. The impervious area in a drainage basin provides a quantitative measure of this potential impact: it is a measure of the total area where water does not infiltrate into the soil, including roads, rooftops, sidewalks, patios and compacted soil. Imperviousness is an integrative indicator, and can be used to estimate or predict cumulative water resource impacts. Research in various regions has consistently shown a strong relation between the imperviousness of a drainage basin and the health of the receiving stream [5,11–13]. Fig. 3 is a generalized description of this relationship, indicating the existence of a threshold at around 10% imperviousness. Effective impervious area, the impervious area directly draining into the stormsewer system or streams (and typically significantly lower than the total impervious area in low density residential areas), is the most appropriate measure of the hydrological impact of urbanization, but total impervious area is the measure used in most studies on the impact of imperviousness on stream health and is considered to be the best indicator to quantify the overall degree of

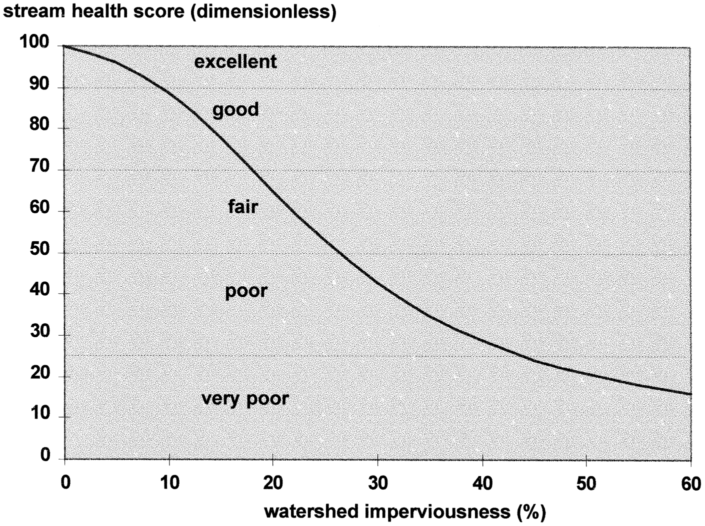

Fig. 3. Generalized relation between watershed imperviousness and stream health.

urbanization versus just hydrological changes. For this reason, total impervious area is used here. Although the use of imperviousness as an integrative indicator has become widely accepted among watershed professionals in North America, it should be emphasized that its use is limited to the subbasin and watershed level scale (from 5 to 150 km^2): at larger scale the indicator is not very appropriate, because of the topographic and landuse heterogeneity typical of large river basins.

2.5. Water quality

Water quality in urban watersheds is an integrative measure of the impact of many stressors in the watershed. Water quality is also a very powerful indicator in determining possible uses of the watershed, including the protection of aquatic life and human uses. Typically water quality is assessed by measuring a wide range of parameters, including pH, dissolved oxygen, temperature, turbidity, alkalinity, conductivity, total and suspended solids, and the concentration of a variety of pollutants, including nutrients, metals and organics. No single parameter is sufficient to adequately express water quality. On the other hand, the enormous amount of data generated by monitoring requires some integration if the results are to be presented meaningfully to local watershed managers and decision-makers and the general public.

For this reason, water quality indices have been developed, which reduce technical water quality information into a simple description on the state of water quality. The British Columbia Ministry of Environment's Water Quality Index was developed in 1994. The index is based on the attainment of water quality objectives, which have been developed for many water bodies in the Province [14]. The WQI is defined as:

$$100-\sqrt{(F_1)^2+(F_2)^2+(F_3/3)^2}\,/1.453$$

F_1: number of objectives not met as % of all objectives checked; F_2: frequency with which objectives not met as % of all instances of objectives being checked; F_3: amount by which objectives not met as the maximum deviation for any one objective.

The factor F_3 was divided by three since testing of the formula indicated that this factor was very dominant in certain datasets. The factor 1.453 assures the maximum value of the formula is 100. The BC Ministry of Environment's formula was modified since values in their formula range from 0 (excellent) to 100 (very poor), while the reverse scale is employed in this study.

Despite some of its obvious limitations, this index was used in the study, primarily since it is familiar to professionals and because it incorporates locally defined objectives. Another index which being used is the National Sanitation Federation Water Quality Index [15]. The use of the WQI is not restricted to any particular scale or type of waterbody: it is, however, very dependent on the objectives which have been set, and should only be discussed in relation to those objectives.

3. Case study data collection and analysis

The general framework and specific procedures described above were applied to the Brunette River watershed, a small urban watershed of 70 km^2 in the Vancouver area of British Columbia, Canada. It is a lowland watershed, dominated by heavy rainfall from November to March and long dry periods in the summer. Human development has had a significant impact on its main ecosystem functions: recreation and habitat for coho salmon and cutthroat trout.

Data from 20 years of research in the watershed was used to derive information on the selected indicators [16–19]. All information was spatially referenced, analysed, integrated and displayed using a Geographic Information System (Terrasoft and Mapinfo) on a 1:20 000 scale. The watershed was divided into 25 drainage areas, using topography and stormwater drainage system maps. Data collection was carried out in such a manner that it would allow for integration at the level of these 25 subbasins. The data-layers include land use, impervious area, streams, riparian vegetation cover, road network, transportation density, point sources, spills and accidents, stormwater contaminant loadings, water quality, sediment quality, fish habitat quality, toxicity bioassay and fish health. Imperviousness was determined in a previous study [17] using aerial photographs of the watershed for 1973 and 1993. Another recent study [16], which monitored baseflow conditions and stormwater events over a 2-year period, provided the basis for the water quality index.

Results from the analysis were organized in a hypermedia program (Toolbook) for presentation and distribution purposes. The use of hypermedia allows for the generation of visually rich electronic documents which serve to better illustrate the spatial and temporal patterns and the complex relationships among variables. Presentations of the results to watershed professionals and decision-makers working in the case-study area have resulted in valuable feedback in terms of conceptual model development, indicator selection and the integration process.

4. Watershed profile results and discussion

The results on the set of indicators are presented in the form of a 'watershed profile', as shown in Fig. 4 for the whole watershed. The figure is constructed using the numerical values for each indicator, but the final profile only uses qualitative descriptions, because the numerical values suggest a higher degree of accuracy than can be achieved—and is required—in this screening level analysis.

The watershed profile for the whole watershed provides a general overview; the individual indicators become a powerful tool in the analysis of spatial and temporal trends. As an example, Fig. 5 compares the imperviousness indicator for the various sub-watersheds. The results indicate that the overall degree of imperviousness is high, which would suggest a low potential for maintaining or enhancing stream health. There is, however, very significant spatial variation, and there are clearly areas which have a much higher potential. Based on this assessment, those high potential areas should be the focus of more detailed studies and have the highest priority in this watershed for management. In addition, riparian corridor vegetation is fairly good across the whole watershed (Fig. 4), suggesting that some of the impacts of high imperviousness are mitigated. Comparison with 1973 aerial photographs suggested fairly minor changes, indicating that most of the urbanization occurred before that time.

Water quality conditions are described in Fig. 6. The Water Quality Index is displayed for winter and summer conditions at baseflow and stormevent conditions. The results indicate fairly good conditions for baseflow in both winter (high flow) and summer (low flow). Seasonal variation was significant, but no clear pattern emerged

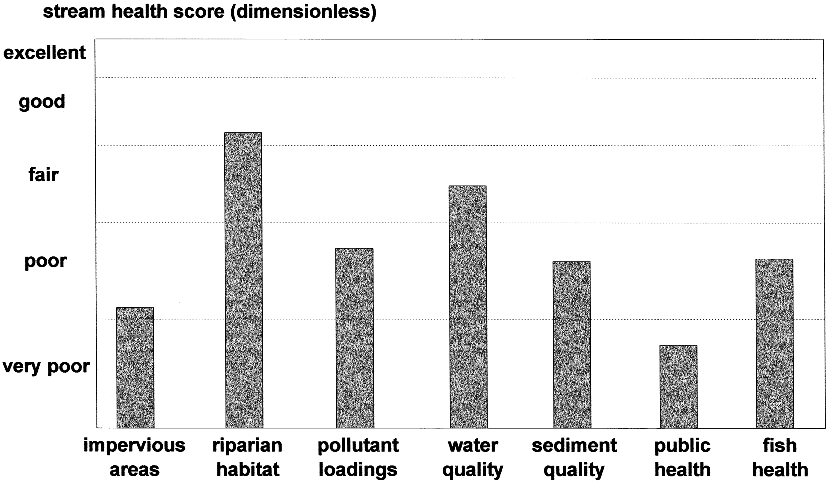

Fig. 4. Watershed profile for the Brunette River Watershed. Detailed (spatial and temporal) analysis has only been carried out for the indicators 'impervious areas' and 'water quality'. The other indicators are based on a preliminary evaluation at the level of the whole watershed and are only shown in this figure to illustrate the types of information presented in a watershed profile. More detailed results on all of the indicators can be found in Ref. [10].

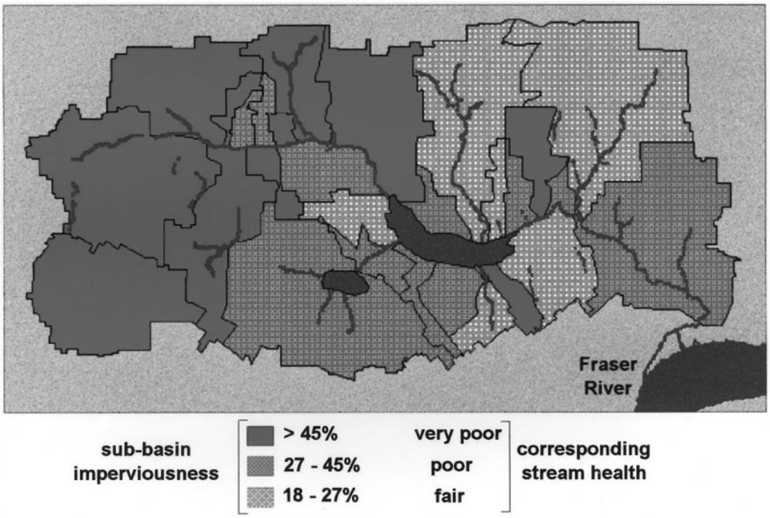

Fig. 5. Imperviousness classification of the Brunette River Watershed. The imperviousness has been determined using 1993 aerial photographs. Imperviousness is expressed here by the total impervious area as a % of the total area of each subbasin. The imperviousness for the whole watershed is 41%. The spatial analysis reveals differences among the various subbasins which are very useful for management: presenting only the total imperviousness would give a very incomplete picture of the watershed.

from the 13 stations. Conditions during storm events were consistently poor to very poor, indicating the importance of stormwater monitoring. Summer storm events also resulted in significantly lower values than the winter events; in summer the rainstorms

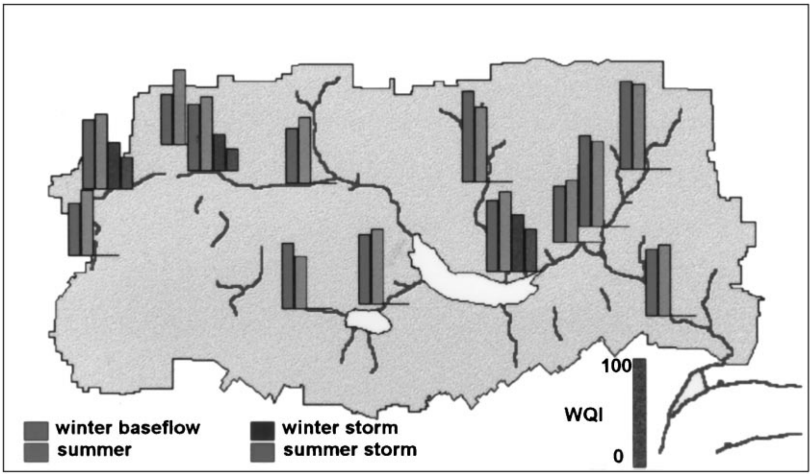

Fig. 6. Water Quality Index for the Brunette River Watershed. The Water Quality Index was calculated for baseflow conditions (13 stations) and storm events (3 stations), both based on 10 sampling dates over a 2-year period. Water quality measurements used in the calculations include: dissolved oxygen, pH, temperature, turbidity, nitrate–nitrogen, total phosphorous, total copper, total lead and total zinc. Many other water quality parameters were measured but not included in the calculations since no objectives have been set.

are much less frequent but more intense than in winter, resulting in the flushing of pollutants that have accumulated.

The Water Quality Index scores came out lowest for the regions with the highest degree of imperviousness, lending some support for the generic relationship between imperviousness and stream health (Fig. 3). No attempt was made to statistically correlate the two indicators at this stage, since there are insufficient datapoints. As Schueler [5] has pointed out, adapting a generic relationship—such as illustrated in Fig. 3—for a particular ecoregion in order to develop more specific management strategies, requires information on several watersheds with a wide range in indicator values.

5. Conclusions

The watershed profile developed in this study can be used as a screening tool for local watershed management: it identifies areas of concern and provides a starting point for a more complete evaluation of the complex relationships in an urban watershed. A relatively high level of integration is achieved by using a small set of key indicators which express the general state of the watershed. This has allowed for a more meaningful communication between scientists, watershed professionals and local decision-makers in the case-study watershed. Spatial and temporal trends in selected indicators can be illustrated effectively using a Geographic Information System, which helps to identify particular regions within the watershed which should receive a higher priority for management.

Acknowledgements

This research was made possible in part by funding from the Fraser River Action Plan (by Environment Canada and the Department of Fisheries and Oceans) and the Tri-Council Eco-Research Project. Gratitudes are extended to all members of the research advisory committee for this study under supervision of Prof. Hans Schreier and to local stakeholders who participated in various workshops.

References

[1] United States Environmental Protection Agency, Guidelines for Ecological Risk Assessment, USEPA, Washington, DC, 1996.

[2] BC Ministry of Forests, Coastal Watershed Assessment Procedure Guidebook (CWAP), BC Ministry of Forests, Victoria, BC, 1995.

[3] J.B. Latour, R. Reiling, Comparative environmental threat analysis: three case studies, Environ. Monit. Assess. 29 (1994) 109–125.

[4] R.A. Claytor, W.E. Brown, Environmental indicators to assess stormwater control programs and practices, Centre for Watershed Protection and US Environmental Protection Agency, Silver Spring, MA, 1996.

[5] T. Schueler, Site planning for urban stream protection, Metropolitan Washington Council of Governments, Washington, DC, 1995.

[6] D.B. Booth, Urbanization and the natural drainage systems—impacts, solutions and prognoses, Northwest Environ. J. 7 (1991) 93–118.

[7] R.D. Klein, Urbanization and stream quality impairment, Water Resour. Bull. 15 (1979) 948–961.

[8] R.R. Horner, D.B. Booth, A. Azous, C. May, Watershed determinants of ecosystem functioning, to be published in: L.A. Roesner (Ed.), Effects of Watershed Development and Management on Aquatic Ecosystems, American Society of Civil Engineers, New York NY, 1997.

[9] ESSA Technologies, Non-point source pollution strategies for British Columbia, Technical report prepared for the BC Ministry of Environment, Victoria, BC, 1996.

[10] P.A. Zandbergen, Urban watershed assessment–linking watershed health indicators to management of urban watersheds, PhD dissertation, Resource Management and Environmental Studies, University of British Colombia, 1998.

[11] T. Schueler, The importance of imperviousness, Watershed Protection Tech. 1 (1994) 100–111.

[12] C.L. Arnold, C.J. Gibbons, Impervious surface coverage: the emergence of a key environmental indicator, J. Am. Planning Assoc. 62 (1996) 243–258.

[13] C. May, Assessment of cumulative effects of urbanization on small streams in the Puget Sound Lowland eco-region: implications for salmonid resource management, PhD dissertation, Department of Civil Engineering, University of Washington, 1996.

[14] BC Ministry of Environment, The British Columbia water quality index, British Columbia Ministry of Environment, Victoria, BC, 1995.

[15] W.E. Ott, Environmental indices: theory and practice, Ann Arbor Science, Ann Arbor MI, 1978.

[16] R.K. MacDonald, K.J. Hall, H. Schreier, Water quality and stormwater contaminants in the Brunette River Watershed, British Columbia, Westwater Research Centre, University of British Columbia, 1997.

[17] D.W. McCallum, An examination of trace metal contamination and land use in an urban watershed, MSc dissertation, Civil Engineering, University of British Columbia, 1995.

[18] G.A. Larkin, Hydrocarbon pollution from urban runoff in the Brunette watershed, MSc dissertation, Civil Engineering, University of British Columbia, 1995.

[19] K.J. Hall, F.A. Koch, I. Yesaki, Trace metals and chlorinated hydrocarbons in the sediments of a metropolitan watershed, Westwater Research Centre, University of British Columbia, 1976.