Changes in Land Uses, Hydrology and Fish Habitats in an Urban Drainage, Cedar River, Washington

Robert C. Wissmar, Raymond K. Timm II

Abstract

This synthesis presents multi-scale approaches for evaluating influences of changing land cover characteristics (e.g., forest and impervious surfaces) on the composition of watershed landscapes, hydrological regimes, habitat restoration and habitats preferred by salmon. Spatially explicit modeling of changes in land covers and flood discharge regimes for urban and rural watersheds are compared for two periods, historical to 1991 and from 1991 to 1998. For the historical to 1991 period, impervious surfaces increase in both urban (range +43% to +71%) and rural (range +8% to +15%) watersheds while forest covers decline (range from – 63% to -83% in urban and from -28% to -34% in rural areas). For the 1991 to 1998 period, impervious areas also show increases, ranging from +4% to +27% in urban and from +38% to +60% in rural watersheds. Land cover changes in urban areas are caused by infilling and continued development in an already urban matrix. In contrast, rural areas lost forests through rapid land conversions characterized by scattered low-density residential, clustered dense commercial, residential developments and increases in transportation facilities near newly incorporated areas. Hydrologic simulations indicate annual flood frequencies increase in all watersheds in response to increases in impervious surfaces and declines in forests. For the historical to 1991 period, flood discharges range from +68% to +169% in urban and from +7% to +21% in rural areas. During 1991 to 1998, smaller percent changes in discharge occur for all watersheds (range from -5% to +17%). Comparison of water yields (discharge per unit area, m yr^{-1}) for watersheds as functions of different impervious and forest land covers (percent of watershed area) indicate two phases of abrupt changes for water yields. The first shows sharp increases in yields when impervious surfaces are between 10% and 23% and forest covers are between 59% and 81%. The second phase shows higher yields that coincide with larger areas of impervious surfaces (between 46% to 74%) and lower forest covers (between 17% and 37%). These relationships indicate that our characterizations of impervious surfaces and forested covers and their use in a spatially explicit hydrology model provides a potent approach for revealing how variations in spatial distributions of different land covers affect stream discharge rates and "thresholds" of water yields. Subsequent land cover evaluations using a multi-scale habitat model identify priority river reaches and floodplain habitats for restoration and conservation. Large patches of positive indices indicate the most favorable habitats are characterized by low fragmentation, greater connectivity and availability to salmon. Factors commonly preferred by spawning salmon (*Oncorhynchus nerka*) are upwellings of subsurface waters, moderate water depths, and gravel/cobble sized substrates.

Keywords: multi-scale, spatial modeling, watershed, hydrology, land cover, habitat, salmon

Introduction

This paper presents a synthesis of multi-scale watershed and ecological modeling studies that evaluate influences of changing land cover characteristics (e.g., forest and impervious surfaces) on the composition of watershed landscapes, hydrological regimes, habitat restoration (e.g., riparian and stream) and habitats preferred by salmon. The study areas include channels, floodplains and tributary watersheds of the lower Cedar River drainage near Seattle, WA (Figure 1). The objectives include: a) evaluating changes in land covers between historical (full forest cover, pre-20th century), 1991 and 1998 conditions; b) determining effects of changing land

---

Wissmar is a Professor and Timm is a Research Assistant at the School of Aquatic and Fishery Sciences, University of Washington, WA 98195. E-mail: wissmar@u.washington.edu.

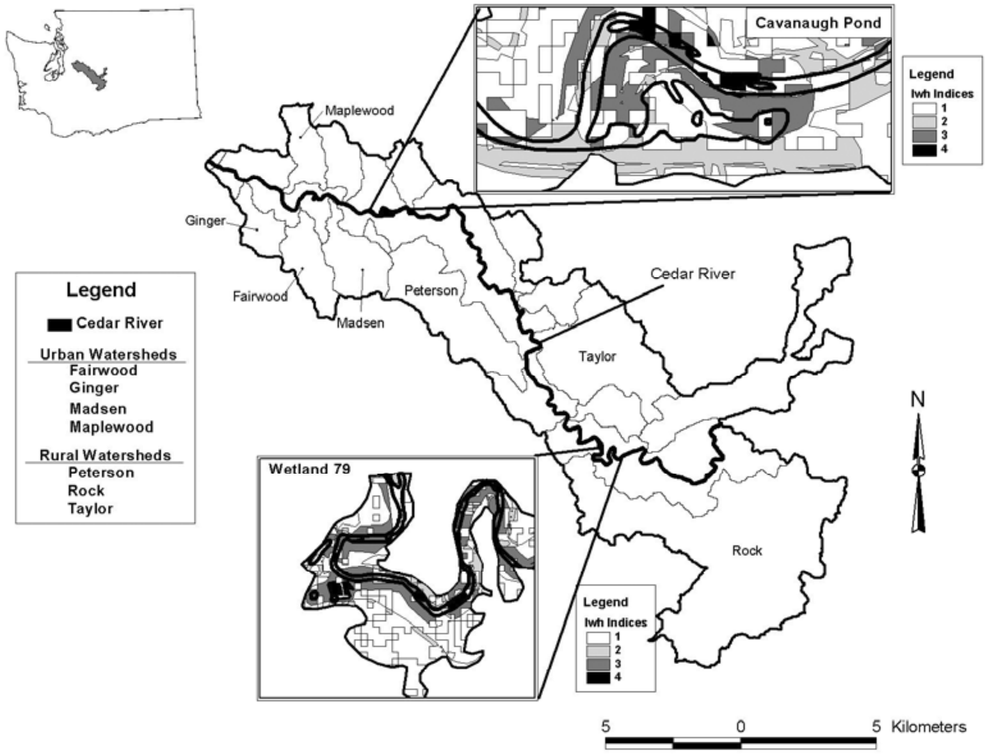

Figure 1. Select urban and rural tributary watersheds of the lower Cedar River, and river reaches and habitats prioritized for restoration and conservation. The urban (Ginger, Maplewood, Fairwood and Madsen Creeks) and rural watersheds (Peterson, Taylor and Rock Creeks) were analyzed to determine changes in land covers between historical ("full forest cover"), 1991 and 1998 conditions and to assess effects of land-uses on hydrological regimes. Spatial distributions and characteristics of positive patch indices (I_{wh}) indicate that Wetland 79 and Cavanaugh Pond are priority floodplain habitats. The Cedar River drains into Lake Washington near Seattle, WA.

uses on hydrological regimes of tributary watersheds; c) using landscape indicators of spatial compositions of co-occurring "natural systems" and human developments to identify opportunities for habitat restoration and conservation; and d) identifying habitat preferences of salmon in order to improve habitat restoration initiatives that facilitate fish recovery. The goal of this research is to couple multi-scale watershed and ecological approaches that can be used by watershed managers. In many coastal areas of North America changes in land-uses and hydrology, and ESA listings of salmon and other species, requires improvements in watershed management efforts designed to conserve and restore environments of declining species.

Methods

A summary for the modeling approaches includes status (newly developed or modified), authors, model type, grid cell size (resolution), spatial extent (km^2, ha, m^2) and simulation time (Table 1). Key data sources and files (forested areas, impervious surfaces and other land covers), that facilitate cross-scale integration and modeling of changes in land covers and hydrology, are developed using classifications of Landsat TM scenes and extensive empirical measurements of landscape patches (Burgan et al. 1993, Logsdon et al. in review). These extensively ground-truthed data sets are inputs for the spatial assessment (Wissmar et al. 2000) of changes in land covers and the application of a spatially explicit hydrology model (Wigmosta et al. 1994). This model evaluates impacts of changing land covers on hydrological regimes of urban and rural tributary watersheds (Wissmar et al. in review). Spatially explicit modeling of changes in land covers and flood discharge regimes for urban and rural watersheds are compared for two periods, historical to 1991 and from 1991 to 1998.

Land cover evaluations using the multi-scale habitat model (Timm et al. in press) that applies different land cover files is used to prioritize habitats for restoration and conservation. The land cover files include four

Table 1. Model characteristics for watershed research in the Cedar River drainage near Seattle, WA. Model descriptions include status N (new) or M (modified), citations, type, grid size, spatial extent and simulation time.

Model	Citations	Model type	Grid size (resolution)	Spatial extent	Simulation time
Changes in land-uses (N)	Wissmar el al. (2000)	Spatial Landscape	30 m	Watershed (km^2)	Decadal
Classifying land covers (M)	Logsdon et al. (in review)	NDVI[a]	30 m	Watershed (km^2)	Decadal
Affects of land-uses on hydrology (M)	Wissmar et al. (in) review)	DHSVM[b]	30 m	Watershed (km^2)	Decadal
Prioritizing restoration areas (N)	Timm et al. (in press)	Spatial Landscape	5 m	Watershed (km^2), reach/ habitat (ha, m^2)	Annual, decadal
Affects of Habitat Factors on fish (N)	Hall et al. (2000) Hall (2002)	Multiple logistic Regression (statistical)	1 m	Habitat (ha, m^2)	Daily, monthly

[a] NDVI classification: Normalized Difference Vegetation Index (Burgan 1993)
[b] DHSVM: Distributed Hydrology Soil Vegetation Model (Wigmosta et al. 1994)

habitat factors (i.e., forest canopy, wetlands, channel configurations and gravel sources) and four anthropogenic factors (i.e., impervious surfaces, real estate values, land zoning and physical channel constraints). Model outputs include habitat indices (I_{wh}) and composition and configuration metrics of habitat indices at the valley floor and reach scales. Homogeneous patches as indices (I_{wh}) of potential sites are measured in terms of their locations, sizes, and relative degree of fragmentation. These patch indices are further analyzed to characterize the intra-patch heterogeneity for combinations of habitat and anthropogenic factors for each grid cell. Model application requires spatial weighting of indices to prioritize riparian zones along salmon bearing streams.

Two priority restoration areas (Wetland 79 and Cavanaugh Pond) are further analyzed to determine habitat preferences of spawning sockeye salmon (*Oncorhynchus nerka*) (Hall et al. 2000, Hall 2002). Logistic regression and electivity models are used to determine preferred habitats of spawning fish. Ground-truthed GIS data sets of aquatic-riparian landscapes and empirical measures of habitats factors (water depth, substrate, detrital depth, subsurface water flow, water temperature, and cover) provided inputs for these models.

Results

Spatial modeling of land cover changes between historical and 1991 and from 1991 to 1998 indicate losses of forest covers and increases in impervious surfaces. For the historical to 1991 period, impervious surfaces increase in both urban (range +43% to +71%) and rural (range +8% to +15%) watersheds while forest covers decline (range from –63% to -83% in urban and from -28% to -34% in rural areas). For the 1991 to 1998 period, impervious areas also increased, ranging from +4% to +27% in urban and from +38% to +60% in rural watersheds (Table 2).

Table 2. Percent change in forest covers, impervious surfaces and annual flood discharges from historical to 1991 and 1991 to 1998 within urban* and rural watersheds of the lower Cedar River. Percent changes for periods are summarized as plus or minus Δ%. Historical conditions (Hist.) assume fully forested cover. See Figure 1 for locations of watersheds. Flood discharges are based on the 10-year recurrence interval.

	Land covers				Annual flood discharge	
	Hist. to 1991		1991 to 1998		Hist. to 1991	1991 to 1998
	Forest	Impervious	Forest	Impervious	Discharge	
Watershed	--- (Δ%) ---		--- (Δ%) ---		--- (Δ%) ---	
Ginger*	-83	+71	+18	+4	+169	+4
Maplewood*	-63	+48	-24	+27	+96	+17
Fairwood*	-63	+46	-3	+17	+84	+3
Madsen*	-63	+43	+19	+9	+68	-2
Peterson	-34	+15	-11	+53	+16	+2
Taylor	-28	+10	-4	+60	+21	+1
Rock	-29	+ 8	+14	+38	+7	-5

Simulations using the spatially explicit hydrology model, where model functions are sensitive to changes in land covers, show increases in flood discharges in urban and rural watersheds. Annual flood frequencies increase in all watersheds in response to increases in impervious surfaces and declines in forests. For the historical to 1991 period, flood discharges ranged from +68% to +169% in urban and from +7% to +21% in rural areas. From 1991 to 1998, smaller percent changes in discharge occur for all watersheds (range from -5% to +17%) (Table 2).

Comparisons of water yields among watersheds are made as a function of different amounts of impervious and forest land covers (percent of watershed area) in the respective watersheds. Water yields, discharge per unit area (m yr^{-1}) for 10 and 25-year recurrences, indicated two distinct phases for abrupt changes in discharge levels during 1991 and 1998. The first phase showed sharp increases in discharge (range from 3.7 to 6.3 m yr^{-1}) when impervious surfaces are between 10% and 23% and forest covers are between 59% and 81%. The second phase occurred at higher discharges (4.1 to 8.7 m yr^{-1}) and coincided with larger areas of impervious surfaces (between 46% to 74%) and lower forest covers (between 17% and 37%).

Land cover evaluations using the multi-scale habitat model demonstrates that patterns and sizes of patch indices can quantify the spatial complexity of habitats within riparian areas and can prioritize habitats for restoration and conservation. Simulations show reaches characterized by high positive indices (I_{wh}) and large patch sizes represent intact-high quality habitats. These habitats are the most favorable for restoration and conservation. Lower positive and negative scores that are influenced by anthropogenic factors are coincident with higher degrees of habitat fragmentation. These spatial configurations show less favorable conditions for restoration and conservation.

Spatial distributions of positive indices and their patch characteristics indicate that specific river reaches and floodplain areas contain high positive indices and relatively low fragmentation. The larger mean patch sizes pointed to less fragmentation and greater connectivity between habitats. Two floodplain sites containing prime examples of priority habitats (high positive indices) include Wetland 79 and Cavanaugh Pond (Figure 1). These floodplain sites and habitats are connected to the main channel of the lower Cedar River by outlet channels.

The two floodplain sites, Wetland 79 and Cavanaugh Pond, are further analyzed to determine habitat preferences of spawning sockeye salmon (Figure 1). The objectives include: a) identifying habitat factors most important to fish selection of redd sites ("egg deposition sites"); and b) using this information to improve habitat restoration initiatives required to facilitate fish reproduction and survival. The necessity for this information relates to the diverse types of habitats required by various fish species and their life history stages. The most frequent habitat factors associated with

Table 3. Summary of habitat preferences of spawning sockeye salmon (*Oncorhynchus nerka*) in two floodplain areas. Floodplain sites include Wetland 79 and Cavanaugh Pond that connect with the main channel of the lower Cedar River near Seattle, Washington. Preferences for habitat types are defined by electivity indices (Hall et al. 2000). The total number of redds at each site are indicated in parenthesis (n). Habitats types indicate major bottom substrate, fluvial and shoreline characteristics (e.g., vegetative cover). Electivity indices (D) calculated as: D = r-p/(r+p)-2rp, where p is the proportion of the habitat available and r is the proportion of the habitat used for redd placement. Electivity values range from +1 (strong selection) to –1 (strong avoidance). Spawning sockeye showed the strongest selection where subsurface waters were upwelling.

Floodplain site	Habitat type	Proportion available (p)	Proportion of redds (r)	Electivity (D)
Wetland 70 (20)	Upwelling	0.13	0.86	+0.95
	Shrub riparian	0.10	0.00	-1.00
	Steep forested	0.22	0.05	-0.71
	Open water	0.55	0.09	-0.85
Cavanaugh Pond (240)	Upwelling	0.11	0.96	+0.99
	Marsh	0.07	0.00	-1.00
	Gravel	0.02	0.00	-1.00
	Island	0.05	0.00	-1.00
	Outlet	0.05	0.04	-0.10
	Open water	0.70	0.00	-1.00

the placement of redds include upwelling of subsurface waters, moderate water depths (10-80 cm), and gravel/cobble substrates (Table 3). Upwelling is the most important factor (electivity indices, +0.95 and +0.99). Relationships between different habitat factors (e.g. upwelling and water temperature, water depth and fine sediments) also influence habitat choices. Favorable intra-gravel flow in redds supplied by upwellings appear to compensate for effects of other sub-optimal habitat attributes. Fish avoid silt and areas with substantial detrital substrates. Fish spawning densities varies between years (1999 and 2000) and appears to affect preferred water depth ranges in both ponds. The identification of habitat factors most important to salmon spawning success in off-channel areas provides a strong ecological basis for improving the design, implementation and evaluation of restoration activities within off-channel and floodplain areas of large river systems.

Conclusions

Our multi-scale approaches demonstrate how analyses using watershed and ecological models can facilitate assessments of influences of land covers on hydrological regimes of watersheds, habitat conditions of riparian and stream ecosystems and habitats selected by fish. Spatial modeling of changes in land covers show losses of forest covers and increases in impervious surfaces. Land cover changes in urban areas are caused by infilling and continued development in an already urban matrix. In contrast, rural areas lost forests through rapid land conversions characterized by scattered low-density residential, clustered dense commercial, residential developments and increases in transportation facilities near newly incorporated areas (Wissmar et al. 2000). Hydrologic simulations indicate annual flood frequencies increase in all watersheds in response to declining forests and increases in impervious surfaces. Flood frequencies within urban watersheds are several times greater than in rural watersheds. Furthermore, comparisons of water yields (m yr^{-1}) for watersheds as functions of different amounts of impervious and forest covers show two distinct phases for abruptly increasing water yields. These relationships indicate that our characterizations of impervious surfaces and forested covers (Wissmar et al. 2000, Logsdon et al. in review), and their use in a spatially explicit hydrology model (Wigmosta et al. 1994, Wissmar et al. in review), provide robust approaches for revealing how variations in spatial distributions of different land covers affect stream discharge rates and “thresholds” of water yields. In summary, both spatial patterns and extent of different land covers influence model dynamics.

Subsequent land cover evaluations using the habitat model show patterns of patch indices that can be used to prioritize habitats for restoration and conservation. Large patch sizes and positive indices indicate the most favorable habitats are those with relatively low degrees of fragmentation, greater habitat connectivity and availability to salmon (Timm et al. 2003). Some important areas include floodplain channels and ponds that contain habitats preferred by salmon. Further analysis using logistic regression and electivity indices (Hall et al. 2000, Hall 2002) indicate that spawning salmon select specific habitat factors (e.g., upwelling waters and gravel substrates). Our ongoing studies are evaluating other models (Timm et al. in preparation, Wissmar et al. in review) that can be used in multi-scale approaches for improving watershed and habitat management and protecting human interests.

Acknowledgments

The authors appreciate reviews by Tom Leschine and Don Gunderson. This research was made possible by a grant from the U.S. Environmental Protection Agency (STAR-EPA: R 827149-01-0) and collaboration with the University of Washington’s Marine Science and PRISM programs, King County, City of Renton, City of Seattle, Washington Department of Fisheries and Wildlife, U.S. Army Corps of Engineers and the U.S. Forest Service.

References

Burgan, R.E., and R.A. Hartford. 1993. Monitoring vegetation greenness with satellite data. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT. General Technical Report INT-297.

Hall, J.L., R.K. Timm, and R.C. Wissmar. 2000. Riparian Ponds as Sockeye Salmon Spawning Habitat in the Cedar River, Washington. In P.J. Wigington and R.L. Beschta, eds., Riparian Ecology and Management in Multi-Land Use Watersheds, Portland, Oregon, August 28-31, 2000, pp. 89-94. American Water Resources Association, Middleburg, VA.

Hall, J.L. 2002. Physical and Biotic Factors Influencing Salmonid Habitat Use in Off-channel Ponds of the Cedar River, Washington: Restoration Implications. M.S. Thesis, University of Washington. Seattle, WA.

Logsdon, M.G., R.K. Timm, R.C. Wissmar, D.C. Pflugh, and P. Storck. Variation of impervious areas and urban watershed hydrology. Journal of Environmental Quality and Management (in review).

Timm, R.K., R.C. Wissmar, J.W. Small, T.M. Leschine, and G. Lucchetti. 2003. Multi-scale prioritization of riparian habitats for restoration and preservation. Environmental Management (in press).

Timm, R.K. Channel and Floodplain Habitat Responses to Different River Discharge and Landscape Conditions. Ph.D. Dissertation (in preparation), University of Washington. Seattle, WA.

Wigmosta, M., L. Vail, and D.P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain. Water Resources Research 30:1665-1679.

Wissmar, R.C., D.C. Pflugh, and R.K. Timm. 2000. Changes in Developed Land Cover (1991-1998): Cedar River, Washington. In P.J. Wigington and R.L. Beschta, eds., Riparian Ecology and Management in Multi-Land Use Watersheds, Portland, Oregon, August 28-31, 2000, pp. 287-292. American Water Resources Association, Middleburg, VA.

Wissmar, R.C., R.K. Timm, and M.G. Logsdon. Effect of land cover change on discharge regimes of urbanizing watersheds. Environmental Management (in review).

Wissmar, R.C., W.N. Beer, and R.K. Timm. Selection of riparian reaches for restoration and protection within erosion-prone landscapes. Ecological Applications (in review).