IMPACTS OF STORMWATER RUNOFF ON COHO SALMON IN RESTORED URBAN STREAMS

Sarah McCarthy, Julann Spromberg, John Incardona, Blake Feist, Jenifer McIntyre, Jana Labenia, Mark Myers, Linda Rhodes, Gina Ylitalo, Tracy Collier, and Nathaniel Scholz
NOAA Fisheries Service, Northwest Fisheries Science Center, Ecotoxicology and Environmental Fish Health Program, 2725 Montlake Blvd. E, Seattle, WA 98112
Laura Reed and Katherine Lynch
Seattle Public Utilities, 700 5th Ave. Suite 4900, Seattle, WA 98124-4018
Jay Davis
US Fish and Wildlife Service, Western Washington Fish and Wildlife Office, 510 Desmond Dr. SE Suite 102, Lacey, WA 98503

These research findings should be considered preliminary as they have not been scientifically peer-reviewed.

INTRODUCTION

Many watershed restoration projects focus on streams running through urban areas that have barriers to fish passage or unsuitable physical habitat for spawning salmonids. Beginning in the late 1990's, agencies in the greater Seattle area began conducting salmonid spawner surveys to evaluate the effectiveness of local stream restoration efforts. These surveys detected a surprisingly high rate of mortality among migratory coho salmon (*Oncorhynchus kisutch*) females that were in good physical condition but had not yet spawned. In addition, adult coho from several urban streams showed a similar progression of symptoms (disorientation, lethargy, loss of equilibrium, gaping, fin splaying) that rapidly led to death of the affected animals. In recent years, pre-spawn mortality (PSM) has been observed in many lowland urban streams, with overall rates ranging from ~25-90% of the fall runs. Although the precise cause of PSM in urban streams is unknown, conventional water quality parameters (i.e., temperature and dissolved oxygen) and disease do not appear to be causal. Rather, the weight of evidence suggests that adult coho, which enter small urban streams following fall storm events, are acutely sensitive to non-point source stormwater runoff containing pollutants that typically originate from urban and residential land use activities. These findings have important evolutionary implications for salmonid restoration and conservation efforts in urban and urbanizing watersheds.

Coho salmon pre-spawn mortality in Longfellow Creek, WA. This female had ~100% egg retention.

OBJECTIVE

Our ongoing objective is to discover the cause(s) and geographical extent of acute coho salmon die-offs in Puget Sound streams.

METHODS

Stream Surveys and Forensic Analyses

Daily stream surveys were conducted during fall 2002-05 to determine presence or absence of symptomatic fish (gaping, loss of equilibrium, fins splayed, spasming) and pre-spawn mortalities. For each affected fish, we recorded the location, species, gender, fork length, weight (with and without gonads), presence or absence of adipose fin, spawning condition, and percent egg retention in females. We collected tissue (brain, blood, gills, bile from live symptomatic fish, liver, pyloric caeca, intestine, heart, kidney) from symptomatic males and females and freshly dead females. Samples were screened for evidence of disease, vitamin deficiency, pesticide exposure, and hydrocarbon exposure.

Population Modeling

Models of established coho populations were constructed to simulate constant and fluctuating levels of PSM that may reflect changes in land use, runoff management or rain events. Supplementation models estimated how many hatchery juveniles may be needed after completing habitat restoration projects to counter ongoing levels of pre-spawn mortality and maintain a designated number of returning adults. All models were constructed with literature data from Puget Sound populations of coho salmon.

Models were based upon a 3 year life history graph (Fig 1), with reproduction occurring at age 3. Models were run for 200 years to assess changes in adult abundance and time to extinction. Initial conditions simulated a stream supporting a population of 300 adults with a stable age distribution. Control conditions exhibited an intrinsic population growth rate of 1.03 (Fig 2). The primary PSM scenarios included: a constant level of PSM each year; variable PSM annually selected from a range with a uniform distribution; and gradually increasing levels of prespawn mortality over time. Supplementation models assessed the number of hatchery smolts needed to compensate for constant PSM losses and maintain 300 adults.

Figure 1. Life history graph and age structured transition matrix for coho salmon. Pink represents reproductive contribution and green represents survival rates.

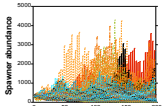


Figure 2. Examples of model runs with variable vital rates under control conditions.

Land Use Analyses

Is there something about the associated watersheds that is correlated with coho PSM events? We defined the area of influence for each index reach as the total area draining into that index reach, which we defined as the catchment. We overlaid the corresponding catchment boundary of the 6 sites with each of the geospatial "habitat" datalayers (Table 1) using ESRI ArcGIS software. We characterized each habitat class/sub-class in the catchment as the fraction of total area of the catchment for each variable. We then ran linear regressions between each of the geospatial datalayer classes/sub-classes in order to quantify the influence of that variable on PSM rates.

Table 1. Summary of types of geospatial datalayers that were used in the spatial analysis.

- Land Use and Land Cover
  - University of Washington Rapid Land Cover Classification (from 1998 LANDSAT imagery)
  - University of Washington Prism Classification (from 2002 LANDSAT imagery)
  - King County Impervious/Impacted Surfaces
  - King County Parcels - Property Type
- Roads
  - Surface Area (estimated)
    - King County Street Network
    - Puget Sound Regional Council (PSRC)
  - Traffic Intensity
    - PSRC Modeled Average Week Day Traffic
    - Washington State Dept of Transportation Mean Daily Vehicle Miles Traveled

Model Overview

Figure 3. Overview of land use model, which overlays GIS Population datalayers with PSM data to predict which land uses will be most highly correlated with PSM.

STUDY SITES

Pre-spawn (top) vs. post-spawn mortality female coho

Potential Causes for Pre-Spawn Mortality

- High temperature/Low dissolved oxygen
- Hydrocarbon exposure
- Pathology and pathogens
- Vitamin deficiency
- Stress and poor condition
- Pesticide exposure
- Other/combination of factors?

FORENSIC RESULTS

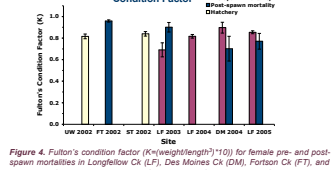


*Figure 4. Fulton's condition factor (K=(weight/length^3)*10)) for female pre- and post-spawn mortalities in Longfellow Ck (LF), Des Moines Ck (DM), Fortson Ck (FT), and University of Washington (UW) and Stillaguamish (ST) hatcheries. Ovaries were removed from all fish prior to weighing. Error bars represent standard error.*

Poor "Condition"

We compared fish condition (Fulton's Condition Factor) among sample streams and hatcheries (Fig 4). No consistent differences were seen among sites and years or between pre- and post-spawn mortalities.

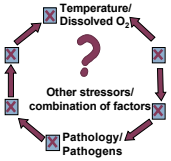
Vitamin Deficiency

We examined thiamine levels in the eggs, liver, and muscle of female coho salmon, but found no significant difference between symptomatic fish in Longfellow Ck and non-symptomatic fish in Fortson Ck or Issaquah hatchery.

Table 4. Preliminary histopathology results for lesions/pathogens potentially associated with coho pre-spawn mortality, 2003-04.

	Longfellow Creek	Des Moines Creek	Elliott Bay	Issaquah Hatchery	Wallace R. Hatchery
GILL	n=21	n=22	n=27	n=24	n=19
Loma salmonis (microsporidian)	24%	9%	7%	13%	5%
HEART	n=21	n=22	n=26	n=24	n=20
Loma salmonis	19%	5%	0%	13%	10%
ANY ORGAN	n=21	n=22	n=27	n=24	n=20
Loma salmonis	29% (but 46% in 2003, 0% in 2004)	9%	9%	17%	10%
TRUNK KIDNEY	n=21	n=21	n=27	n=23	n=20
Nanophyetus salmincola (digenetic trematode, metacercaria)	10%	19%	19%	0%	0%
Tubular protein casts, necrosis	5%	52%	0%	4%	0%
LIVER	n=20	n=22	n=27	n=21	n=18
Hydropic degen. hepatocellular coagulative necrosis	25%**	36%* **	0%	19%	17%
Hepatocellular megalocytosis, nuclear alterations	15%* **	9%**	0%	0%	6%

*indicates significantly higher prevalence than at the combined sites of Elliott Bay, Wallace River, and Issaquah Creek hatcheries, by the Fisher's Exact Test
**indicates significantly higher prevalence than at the combined sites of Longfellow Creek and Des Moines Creek than at the combined sites of Elliott Bay, Wallace River, and Issaquah Creek hatcheries, by the Fisher's Exact Test



Stream temperatures in Longfellow Creek during fall 2003 averaged 9°C (range: 3-17°C) and dissolved oxygen averaged 8.1 mg/L (range: 5.4-12.7 mg/L). These values fell within the ranges of tolerable temperature and dissolved oxygen levels for salmonids.

We assessed for prevalences of tissue lesions of both noninfectious and infectious etiology by histopathology, and for pathogen infection prevalences with species-specific PCR. Certain lesions and pathogens were detected (Tables 3 and 4); however, the impacts of these lesions and pathogens on the metabolic or physiological condition of spawning fish are currently unknown.

Table 2. Concentrations of metabolites of polycyclic aromatic compounds measured in bile of returning coho salmon.

Collection year	Collection site	number of fish (samples) (n)	Equivalents of fluorescent aromatic compounds (ng/g bile, wet weight) Pyrene	BaP	Equivalents of fluorescent aromatic compound (ng/mg protein) PAH	BaP
2002	Fortson Creek	10	29 ± 7.0	390,000 ± 100,000	380 ± 130	1,700 ± 600	12 ± 2.7
	Longfellow Creek	6	81 ± 8.9	1,000,000 ± 310,000	23,000 ± 3,900	24,000 ± 5,200	310 ± 60
	p value[a]		**0.0099**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
2003	Elliott Bay (a)	12	9.5 ± 0.78	100,000 ± 42,000	2,700 ± 1,000	12,000 ± 5,200	320 ± 130
	Wallace River hatchery (b)	5	3.1 ± 0.39	120,000 ± 30,000	1,300 ± 300	6,500 ± 1,500	110 ± 30
	Longfellow Creek (c)	11	21 ± 3.9	960,000 ± 200,000	20,000 ± 4,600	58,000 ± 13,000	1,000 ± 200
	p value[a]		**< 0.0001**	**0.0012**	**0.0063**	**0.0023**	**0.0005**
	Tukey-Kramer HSD results		a,b,c	a,c; b,c	a,c; b,c	a,c; b,c	a,c; b,c
2004	Des Moines Creek	8	63 ± 9.8	390,000 ± 100,000	6,300 ± 1,300	8,200 ± 1,500	100 ± 25
	Longfellow Creek	2	48 ± 18	420,000 ± 130,000	7,900 ± 2,500	9,400 ± 2,300	200 ± 150
	p value[a]		0.4210	0.6222	0.5175	0.5023	0.1514

[a] Reported on one statistically, bile
[b] Concentrations in part per billion (ng/g) based on total area compared to the fluorescence of phenanthrene standard at 260/380 nm wavelengths
[c] Concentrations in part per billion (ng/g) based on total area compared to the fluorescence of benzo(a)pyrene standard at 380/430 nm wavelengths
[d] Significant differences (ANOVA, $p < 0.05$) in concentrations of PAC metabolites and protein values based on site are shown in bold.

Hydrocarbon exposure

Preliminary bile analyses for phenanthrene equivalents and benzo(a)pyrene equivalents indicate higher hydrocarbon exposure in Longfellow Creek than in Elliott Bay; and higher exposure in Elliott Bay than in Fortson Creek (Table 2).

Pesticide Exposure

We tested acetylcholinesterase activity in coho brain and muscle and found no significant reduction in AChE activity between reference and urban streams, indicating low exposure to AChE-inhibiting pesticides.

Table 3. Prevalence of infection with indicated pathogen by sampling site and year. Number of fish examined is in parentheses. N.D. indicates assay was not performed.

	C. shasta posterior GI	P. ovalis/varivorus kidney	L. salmonae gill	T. bryosalmonae kidney	N. salmincola kidney	R. salmoninarum kidney
Wallace River Hatchery, 2003	0.0 (20)	95.0 (20)	100 (20)	5.0 (20)	40.0 (20)	0.0 (20)	30.0 (20)
Issaquah Hatchery, 2003	4.2 (24)	87.5 (24)	79.2 (24)	4.2 (24)	0.0 (24)	0.0 (24)	33.3 (24)
Duwamish River, 2003	18.5 (27)	100 (27)	7.4 (27)	14.8 (27)	7.4 (27)	48.1 (27)	22.2 (27)
Longfellow Creek, Early 2004	0.0 (14)	100 (14)	50.0 (14)	85.7 (14)	14.3 (14)	35.7 (14)	35.7 (14)
Longfellow Creek, Late 2004	N.D.	0.0 (7)	0.0 (6)	0.0 (8)	0.0 (7)	N.D.	85.7 (7)
Des Moines Creek, 2004	N.D.	0.0 (14)	0.0 (22)	4.5 (22)	0.0 (14)	N.D. (14)	100 (14)

ABUNDANCE MODELS

Constant levels of PSM above 60% caused a very rapid population decline (Fig 5, Table 5), when vital rates varied within their normal distributions. Gradually increasing the levels of PSM allowed the populations to persist longer than in the constant impact scenarios. The rapid increase to 80% prespawn mortality resulted in extinction at 27 years and the slow increase to 35% prespawn mortality model was extinct in 64 years (Table 5). Varying PSM within a range between 0 and 20% resulted in 75% of the 500 runs conducted ending in local extinction, on average at 154 years (Table 5). Allowing PSM to range from 0 to 90% resulted in 100% local extinction at an average time of 32 years (Table 5).

The restoration models provided an estimate of the number of year old juveniles that would need to be released to provide 300 spawners, after the effects of PSM had been incorporated. An area estimated to have 30% PSM would need approximately 30% of the smolt needed to establish the population planted each year to maintain the target spawning population abundance (Fig 6).

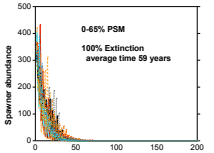


Figure 5. Examples of model runs with variable vital rates over 200 years under variable PSM conditions.

Table 5. Percent of runs extinct, and mean and minimum time to extinction under constant PSM, annually varying PSM and gradually increasing PSM.

% PSM	% of Runs Extinct within 200 y	Time to Extinction (Std Dev)	Minimum Time to Extinction
Constant			
0	0	NA	NA
5	7	176 (20.5)	130
10	79	155 (23.7)	99
15	99.8	116 (21.6)	73
20	100	84 (14.7)	47
25	100	66 (10.0)	40
30	100	53 (6.7)	40
35	100	44 (5.4)	31
40	100	38 (3.9)	29
45	100	33 (3.2)	26
50	100	29 (2.7)	23
55	100	25 (2.3)	20
60	100	23 (1.8)	18
65	100	20 (1.6)	17
70	100	18 (1.3)	15
75	100	16 (1.3)	14
80	100	15 (0.6)	12
85	100	13 (1.2)	12
90	100	12 (0.3)	10
95	100	9 (0.5)	9
Uniform distribution			
0-20	79	154(26.8)	78
20-50	100	44 (5.8)	30
0-90	100	28 (5.2)	15
70-90	100	14 (1.4)	12
Gradual increase			
80% over 20 y	100	27 (1.2)	24
35% over 35 y	100	64 (6.5)	46

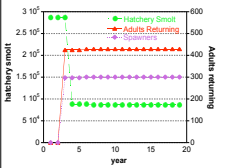


Figure 6. Number of hatchery smolts needed to compensate for 30% PSM and maintain 300 spawners.

LAND USE ANALYSES

There were many habitat variables that had high R^2 values from the regression analyses. Therefore, we only screened those variables that had an associated p-value of 0.05 or less. There were 17 variables that met our criteria for significance (Table 6) from an initial pool of 46. Most of these variables were different measures of road type and area. We concluded that the total area of non-local (arterials, highways, etc.) as measured by the PSRC data source was the best choice for building a predictive spatially explicit model. To build the predictive model, we applied the equation form the linear regression for the PSRC non-local roads variable to each polygon in an existing sub-watershed hydrologic unit map. This gave us a predictive map (Figure 7) of pre-spawn mortality rates for the central eastern Puget Sound drainage area. Not surprisingly, the highest pre-spawn mortality rates are clustered around the major metropolitan areas of eastern Puget Sound. In addition, there are large areas in the basin that are expected to experience 35 – 100% pre-spawn mortality rates.

Table 6. Preliminary GIS analyses using land use/land cover data indicate a strong relationship between impervious surfaces and pre-spawn mortality.

	Potential Predictor Variable	Adj. R^2	P value
UW Rapid Land Cover Classification (1998 LANDSAT)	Forested	0.755	0.015
UW Prism Classification (2002 LANDSAT)	Mixed Deciduous	0.859	0.005
	Total Forested*	0.766	0.014
King County Street Network	% Non-Local	0.903	0.002
	% Minor	0.889	0.003
	% Surface	0.769	0.014
	% Freeway	0.616	0.046
Puget Sound Regional Council (PSRC)	% Non FC0	0.925	0.001
	% FC14	0.926	0.001
	% Road Surface	0.846	0.034
PSRC Modeled Average Week Day Traffic	PSRC FC16	0.925	0.001
	PSRC FC14	0.665	0.036
	PSRC Total VMT	0.586	0.047
Washington State Department of Transportation Mean Daily Vehicle Miles Traveled	WSDOT FC14	0.861	0.008
	WSDOT FC16	0.820	0.008
	WSDOT Total VMT	0.673	0.028
	WSDOT Non-FC0	0.625	0.038

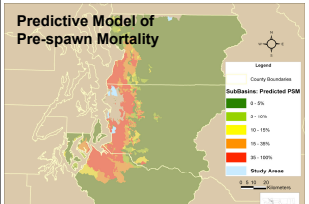


Figure 7. Predictions of female coho salmon pre-spawn mortality based on relationships between study streams and land use. Areas with higher densities of non-local roads were predicted to have higher rates of pre-spawn mortality.

EMBRYONIC DEVELOPMENT

To investigate the effects of urban stormwater runoff on coho embryos, we constructed a constant-flow bypass system allowing the incubation of embryos in untreated stream water and water filtered using sand, activated charcoal, and UV light. Embryos exposed to untreated stream water had consistently higher rates of developmental defects and mortality when compared to embryos raised in filtered water (Fig 8).

Population models were modified to incorporate effects of embryonic mortality. Coho populations were estimated to go extinct within an average of 32 years when both adult and embryonic mortality ranged between 0 - 65%.

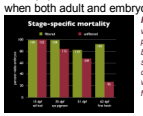
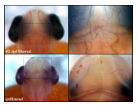


Figure 8. Whitlock-Vibert boxes containing about 150 embryos each were subsampled weekly from each shed. Data represents the percentage of viable embryos from each time-point (N at top of each bar). No differences were observed during early developmental stages, but mortality dramatically increased in the unfiltered water during the eyed stages after 35 days post-fertilization (35 dpf). There were no differences in temperature or dissolved oxygen between filtered and unfiltered water.



A high percentage of embryos with vascular defects in the brain were observed in the unfiltered water at the point where mortality ensued. Surviving alevins at later stages were significantly smaller or developmentally delayed.

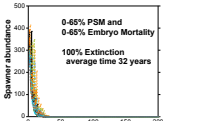


Figure 9. Spawner abundance and extinction time for models incorporating both PSM and embryo mortality. Each impact varied annually between 0 and 65%.

PRECIPITATION / CLIMATE

After a dry period in the early fall of 2002, adult coho began returning with the first major rains in early November. All of the females returning to the stream in the first few days died before spawning. Successful spawners were only observed after several significant rain events. The overall rate of female PSM for 2002 was ~90%, and appeared to be linked to the periodicity of rainfall (Fig 10).

We also measured rainfall at Longfellow Creek between 2002-05, which revealed strong correlations between PSM rates and cumulative rainfall (Fig 11). PSM was higher in the years with less rainfall and lower in the wetter years.

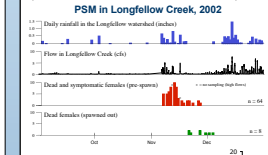


Figure 10. Pre- and post-spawn mortality among adult female coho salmon returning to spawn in Longfellow Creek, Seattle, Fall 2002. Peaks in flow that did not correspond with storm events were related to tidal influence.

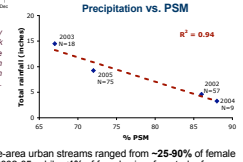


Figure 11. Percent pre-spawn mortality versus cumulative rainfall at Longfellow Creek (2002-05). Precipitation was measured one week before the first coho entered the stream to the last day a coho salmon was observed in the stream.

CONCLUSIONS

- Pre-spawn mortality rates in Seattle-area urban streams ranged from **~25-90%** of female coho returning to spawn between 2002-05, while **<1%** of females in a forested reference stream died prior to spawning.
- Symptoms included disorientation, gaping, lethargy, splayed fins, and loss of equilibrium.
- Water quality parameters (i.e. temperature, dissolved oxygen, etc.) were within a reasonable range for salmonid survival.
- Although prevalences of certain pathogens and tissue lesions were higher at urban sites, these conditions were not consistently found, and the low severity of these lesions or infections suggests that they are unlikely to be causally related to PSM.
- Basic coho models incorporating PSM demonstrate the potential for rapid loss of localized populations in urban streams from non-point and stormwater sources.
- Other evolutionary implications of PSM include selection for coho that return to spawn later in the season, and therefore for potential for interspecific competition between coho and other species that also spawn later (i.e. chum).
- Based on our spatial analyses of land cover in the associated catchments of six different streams, we have concluded that there is a strong correlation (R^2 ~ 0.93) between the total area of non-local roads and coho PSM rates.
- Embryos exposed to unfiltered stream water had higher rates of developmental defects and mortality than embryos exposed to filtered stream water.
- Subsequent yearly surveys in Longfellow Creek (02-05) revealed a significant relationship between the timing and intensity of precipitation events and PSM (R^2 = 0.94).
- **At this time, we do not know the precise cause(s) of coho pre-spawn mortality.**

Acknowledgments

NOAA Fisheries/NWFSC:
Bernie Anulacion, David Baldwin, Cheryl Brown, Jon Buzitis, Cliff Church, Jamie Colman, Heather Day, Barb French, Andy Hall, Karrie Hanson, Laurie Hopkins, Whitney Blanchard, Lyndal Johnson, Cathy Laetz, Jennifer Lanksbury, Tiffany Linbo, Sarah Monkey, O. Paul Olson, Karen Pecks-Miller, Sean Sol, Frank Sommers, Carla Stehr, Gladys Yanagida, Dan Orr

Seattle Public Utilities:
Jose Agudelo, Jo Arnold Philipp, Sandra Brown, Julie Hall, Mike Cooksey, Melissa Martin, Scott Olmstead, Scott Reese, Michael Hinson, Louise Kulzer, Tanyn Sass, Sharon Shamp, Brent Smith, Joe Stanstead, Ellen Stewart, Clarke Thurmon, Jean White, Ryaan-Marie Woods, Kevin McCracken, Beth Schmoyer

Thanks also to:
Stillaguamish Tribe, Washington Trout, WA Department of Fish and Wildlife, Univ. of Washington (E. Gallagher, D. Rose), Adopt-A-Stream Foundation (M. Stiefel, B. Brown), Friends of the Hylebos Wetlands (C. Carter), City of Federal Way (P. Buckli), City of Bellevue (K. Paulsen), Taylor Associates, Inc., US Geological Survey (J. Ebbert, Sandra Embrey), King County (D. Wilson, L. Reinelt, F. Grothkopp, D. Funke, D. Smith), King Conservation District

US Fish & Wildlife Service:
Paul Arnold, Jennifer Quan, Tamara Black, Cindy Schwindler, Ginger Phalan, Jeff Lutchaut, Judy Lantor, Dave Zajac, Mary Mahaffy, Sally Butts, Brian Missildine, Taylor Pittman

Funding support:
City of Seattle, Seattle Public Utilities
NOAA Coastal Storms Program
NOAA Coastal Services Center
USFWS Environmental Contaminants Program
NOAA Oceans and Human Health Initiative