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Modeling effects of climate change on Yakima River salmonid habitats

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Abstract We evaluated the potential effects of two climate change scenarios on salmonid habitats in the Yakima River by linking the outputs from a watershed model, a river operations model, a two-dimensional (2D) hydrodynamic model, and a geographic information system (GIS). The watershed model produced a discharge time series (hydrograph) in two study reaches under three climate scenarios: a baseline (1981–2005), a 1-°C increase in mean air temperature (plus one scenario), and a 2-°C increase (plus two scenario). A river operations model modified the discharge time series with Yakima River operational rules, a 2D model provided spatially explicit depth and velocity grids for two floodplain reaches, while an expert panel provided habitat criteria for four life stages of coho and fall Chinook salmon. We generated discharge-habitat functions for each salmonid life stage (e.g., spawning, rearing) in main stem and side channels, and habitat time series for baseline, plus one (P1) and plus two (P2) scenarios. The spatial and temporal patterns in salmonid habitats differed by reach, life stage, and climate scenario. Seventy-five percent of the 28 discharge-habitat responses exhibited a decrease in habitat quantity, with the P2 scenario producing the largest changes, followed by P1. Fry and spring/summer rearing habitats were the most sensitive to warming and flow modification for both species. Side channels generally produced more habitat than main stem and were more responsive to flow changes, demonstrating the importance of lateral connectivity in the floodplain. A discharge-habitat sensitivity analysis revealed that proactive management of regulated surface waters (i.e., increasing or decreasing flows) might lessen the impacts of climate change on salmonid habitats.

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1 Introduction

The Yakima River is a 5th-order stream in south-central Washington draining approximately 15,851 km². Originating in the Cascade Mountains, the Yakima River flows southeasterly for 346 km to its confluence with the Columbia River near Richland (Fig. 1). Precipitation in the Yakima River Basin varies from 356 cm annually in the Cascades to less than 25 cm in the Kennewick area, making water a scarce commodity during summer months at low elevations. In 1905, the Yakima Project was authorized, with six federal reservoirs constructed between 1910 and 1933. The Yakima River is an important spawning and rearing area for numerous salmonid species and stocks, including fall coho *Oncorhynchus kisutch*, spring and fall Chinook salmon *O. tshawytscha*, summer steelhead *O. mykiss*, and bull trout *Salvelinus confluentus*. Once numbering in the hundreds of thousands, the number of adult anadromous salmonids returning to spawn in the Yakima River Basin has been reduced by over an order of magnitude due to anthropogenic causes (USBR 2002). While irrigation and flood control historically took precedent, reservoir operations, instream flows, and anadromous fish requirements are now also considered at certain times of the water year (USBR 2002).

Climate change, water availability, and fish conservation concerns prompted two important studies in the Yakima River Basin. The first study examined how different water-storage/flow scenarios might affect salmonid habitats in five floodplain reaches of the Yakima River (Bovee et al. 2008). The authors used a two-dimensional (2D) hydrodynamic model (River2D; Steffler and Blackburn 2002) to calculate the velocities, depths, and Froude values for a range of flows (~5 %–95 % exceedance), in a 3X3-m grid spacing. An expert panel of regional fish biologists provided information on salmonid species, life stages, and habitat preferences reach by reach, using a Delphi consensus approach (Zuboy 1981). Fish-habitat models were created by linking the 2D flow simulations with habitat criteria provided by the expert panel in each cell, by flow. The authors demonstrated how flow management (i.e., regulated flows) affects the availability and distribution of fish habitat. A second study employed a calibrated watershed model (Mastin and Vaccaro 2002) to simulate how unregulated surface runoff that occurred under baseline temperatures (1981–2005) might change if the mean annual air temperature increased by 1 °C (P1 scenario) or 2 °C (P2 scenario) relative to baseline (Mastin 2008). The author found that each climate scenario produced a unique hydrograph (discharge time series), with the P1 and P2 scenarios producing increased flows in late fall and winter, and reduced flows in late spring and summer.

Our study built upon previous studies by examining how climate change may affect coho and fall Chinook salmon habitat in the Gap and Wapato reaches. The USBR modified the three unregulated hydrographs (baseline, P1, P2) output from the watershed model with RiverWare™ (Zagona et al. 2001), applying Yakima River operating rules specified in the Interim Comprehensive Basin Operating Plan (USBR 2002; Chris Lynch, personal communication). Relying on a fish expert panel (Bovee et al. 2008), we modeled four life stages of coho salmon (spawning, fry, summer rearing, winter rearing) and three life stages of fall Chinook salmon (spawning, fry, spring rearing). Fall Chinook salmon juveniles emigrate from the Yakima River in late spring at age-0, while coho salmon stay to overwinter and emigrate the following spring at age-1. We examined main stem and side channels separately since they often provide different amounts of rearing and spawning habitats for each species (Brown and Hartman 1988; Swales and Levings 1989; Sommer et al. 2001; Limm and Marchetti 2009). We assessed model sensitivity by simulating an increase in spring and summer flows in the Wapato reach, while decreasing them in the Gap reach. We conclude by providing useful information aimed toward mitigating, restoring, and enhancing salmonid habitats that may be affected by climate change in the Yakima River Basin.

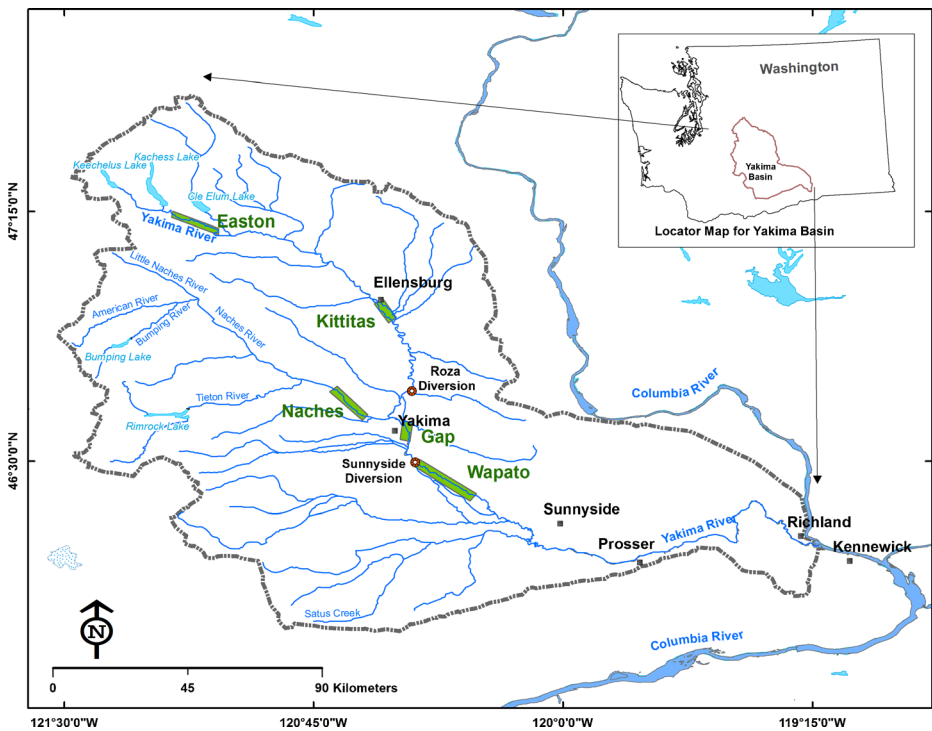


Fig. 1 The location of five reaches that were identified as important to salmonids in the Yakima River in south-central Washington (Snyder and Stanford 2001; Bovee et al. 2008). The two lower reaches (Gap and Wapato) are the focal areas highlighted in our study

1.1 Study site

The Gap and Wapato reaches, located in Yakima County in Central Washington, have broad floodplains and extensive side channels that are important to spawning and rearing salmon (Snyder and Stanford 2001; Stanford et al. 2002). The Gap reach is a large floodplain (1,592 ha) located between the Naches–Yakima confluence and Union Gap, a channel constriction approximately 14 km downstream (Fig. 1). Despite extensive urban encroachment and revetment, there are numerous secondary channels in this reach that remain interconnected at moderate discharges (Bovee et al. 2008). The Wapato reach has a total valley length of approximately 35 km, extending from Union Gap to the confluence of Satus Creek, near Sunnyside, Washington (Fig. 1). At 3,969 ha (1999 measurement), the Wapato floodplain is the largest of the floodplains in the Yakima Basin (Snyder and Stanford 2001). The modeled section of the Gap reach starts at river km 178, at an elevation of 302 m, and ends at river km 172, at an elevation of 287 m. The modeled section of the Wapato reach starts at river km 166, at an elevation of 273 m, and ends at river km 145, at an elevation of 240 m.

Due to irrigation uses and operational strategies (USBR 2002), the Sunnyside and Roza diversion dams create different seasonal and annual hydrographs in the Gap and Wapato reaches, even though the two reaches are almost continuous. For example, the Gap reach, headed by the Roza Diversion Dam, has a 5 % exceedance flow of 220.9 cms (i.e., only 5 % of all flows exceed this value), a 50 % exceedance flow of 79.3 cms, and a 90 % exceedance flow of 35.4 cms (i.e., 90 % of all flows exceed this value). The Wapato reach, headed by the

Sunnyside Diversion Dam, has a 5 % exceedance flow of 204.2 cms, a 50 % exceedance flow of 35.4 cms, and a 90 % exceedance flow of 9.6 cms. Both of these reaches have confined channels due to levees and roads in multiple locations, resulting in 90 % exceedance flows being confined largely in the main channels. As flows approach a 5 % exceedance level, the reaches behave differently due to differences in channel morphology. The Gap reach braids into multiple large side channels, but is still confined by roads and levees at the margins. In the Wapato reach, the braided channel is more pronounced with many large and small side channels extending out to cover a much wider floodplain. Both of these reaches are dynamic in that large flow events (> 283 cms) cause channel shifting in side and main channels, with more movement evident in the Wapato reach than in the Gap reach.

2 Methods

2.1 Modeling overview

A habitat time series is the basic building block required to quantify the effects of alternative hydrographs on targeted salmonid habitats (Bovee et al. 1998). Constructing a habitat time series requires a time series of discharges (either baseline or alternative) and a relationship between discharge and habitat area (discharge-habitat function). For every discharge in the flow series, there is a corresponding habitat value from the discharge-habitat function. The watershed model (Mastin 2008) provided the three unregulated hydrographs (baseline, P1, P2), RiverWare™ modified them with Yakima River operational rules (e.g., storage, diversions, minimum flows), while an expert panel provided fish habitat criteria for each species and life stage (Bovee et al. 2008). Once the datasets were assembled, we evaluated the effects of climate change on salmonid habitats in the Yakima River in four steps. First, we compared and contrasted the three discharge time series modified by RiverWare™. Second, we generated discharge-habitat functions for each salmonid life stage. Third, we created a habitat time series for each salmonid life stage for each scenario (baseline, P1 or P2). Fourth, we explored the sensitivity of each habitat time series by swapping (substituting) the regulated hydrographs in the Gap and Wapato reaches and recomputing habitat. Our approach was theoretical in order to increase our understanding of a complex aquatic ecosystem and our simulations should be viewed with this goal in mind.

2.2 Discharge time series

We determined if our simulated hydrographs under the two climate change scenarios were significantly different from baseline conditions. We compared the shapes of the three regulated hydrographs obtained under baseline, P1 or P2 scenarios, within and between reaches, with a two-sample nonparametric Kolmogorov-Smirnov (KS) test ($\alpha=0.05$; SPSS). Since the Gap reach is directly above the Wapato reach, differences in Z scores between simulations (e.g. baseline vs. P2, or P1 vs. P2) are solely attributable to river operational rules and climate change. We examined magnitude and persistence of summer flows since they have a direct bearing on the creation and management of fish habitat in the Yakima River Basin.

2.3 Discharge-habitat functions

After averaging mean daily flows between 1981 and 2005 for each climate simulation (baseline, P1, P2), we used a cell-based modeler (GRID; ESRI 1992) and habitat criteria to

identify fish habitat on a cell-by-cell basis, over a range of steady-state flows in the Gap (28.317–283.168 cms) and Wapato (8.495–424.753 cms) reaches. Habitat criteria provided by an expert panel (Bovee et al. 2008) and the Delphi technique (Zuboy 1981) produced rule-based rather than statistical models of fish habitat. Thus, a location either was or was not habitat depending on water depth, velocity, or channel location. For each flow-based simulation, we combined spatially explicit velocity and depth grids that were produced from a 2D hydraulic model (Bovee et al. 2008) and habitat criteria to determine which cells met the minimum habitat criteria.

We applied the following rules when identifying and quantifying fish habitat. Cells were not considered habitat if they were disconnected from the river at high flow since they would become ever more isolated at lower flows. Conversely, isolated pools in low-water disconnected side channels were considered habitat provided they were connected to the river at a high flow. This approach allows for fish entering stream reaches at higher flows that may subsequently have become isolated at lower flows, while not permitting areas to be considered habitat if fish could not access them at the highest flows.

For our spawning analysis, we only considered cells to be habitat where the Froude number (a dimensionless measure of stream power) was between 0.3 and 0.6 (i.e., riffle habitat) at the highest flow modeled. The rationale for the Froude-number filter is that stream power forms the gravel/cobble complexes (i.e., spawning substrate) at higher flows, while spawning occurs in such complexes at smaller flows (Bovee et al. 2008). An additional criterion for fry habitat was that only locations within three meters of shore were considered habitat (provided they still meet the depth and velocity criteria) since salmonid fry generally seek shallow, slow water (Moore and Gregory 1988; Muhlfeld et al. 2001). Following completion of the habitat simulations for each flow (~5 %–90 % exceedance), we regressed habitat quantity on stream flow and used a curve-fitting routine to select the best statistical relationship (e.g., linear, polynomial, exponential). We summarized habitat by flow in the main stem and side channels separately, and combined. This allowed us to quantify the relative contribution of each channel domain on salmonid habitat, and to develop separate discharge-habitat functions for main stem, side channels, and combined.

2.4 Habitat trajectories

Simulating the effects of climate change on salmonid habitat required that we link the discharge-habitat functions developed under steady-state flows to the unsteady-state hydrographs produced from baseline, P1, and P2 simulations. We populated the discharge-habitat functions with average daily flows for a given hydrograph on a daily time step with a statistical program (SPSS, Chicago, Illinois). For example, fall Chinook salmon spring rearing extended from May 1 – June 1, or 32 days. For coho salmon winter rearing, the mean daily time series was 213 days (October 1 – April 30). Our technique produced habitat time series that were ideally suited for box-and-whisker plots and line graphs. By displaying the two graphs side-by-side, we could effectively see how the habitat responses differed for each climate scenario from a temporal perspective. The greater the spread in each hydrograph (by life stage, species, reach), the further apart the 25th and 75th quartiles were; the further apart the medians, the larger the difference in habitat. In contrast, line graphs allowed us to see the temporal and spatial patterns in habitat, such as whether the future responses crossed the Y axes of the baseline simulations, diverged, converged, paralleled, or differed little.

We examined four distinct life stages for two species in two reaches, under P1 and P2 scenarios, resulting in 28 possible discharge-habitat responses. We standardized the habitat responses by subtracting each future simulation's (P1 or P2) mean daily habitat value from the

baseline mean daily value and divided the two quantities (change/mean). We created a bar graph to depict habitat response to climate change by life stage and reach.

2.5 Sensitivity analysis

We examined the sensitivity of our models by swapping the Gap and Wapato reach hydrographs (i.e., substituting one for the other) and recalculating habitat under baseline and future scenarios, resulting in 42 unique discharge-habitat combinations. Given that the two hydrographs are different largely due to anthropogenic factors (i.e., Sunnyside and Roza diversions) our approach was useful in determining how fish habitat might change under a modified hydrograph. The Gap reach is held artificially high in the spring and summer months (Roza diversion) while the Wapato reach is artificially low (Sunnyside diversion). Thus, the real effect of swapping the hydrographs was to simulate an increase in flows in the Wapato reach during spring and summer months while decreasing them in the Gap reach.

3 Results

3.1 Discharge time series

There were significant differences ($Z > 2$; $\alpha < 0.05$) in the daily discharge time series under baseline, P1 and P2 climate scenarios, with P2 exhibiting the largest differences (Fig. 2). The Wapato reach was more affected by P1 or P2 scenarios than Gap reach, but both reaches had a relatively similar response between the P1 and P2 scenarios. The winter flows (Dec – Feb) for both reaches were predicted to be larger than baseline flows, with the largest differences observed in January and February. In contrast, spring flow simulations (March – May) were mixed, with early spring showing increased future flows under P1 or P2 scenarios, while late spring had decreased flows compared with baseline. Summer flows are expected to be smaller in the Gap reach all summer, with the largest differences occurring earlier, while only early summer flows are expected to be significantly smaller in the Wapato reach before equalizing with the baseline flow. However, the baseline flow in the Wapato reach is expected to occur approximately 3 weeks earlier under the P1 scenario, and 6 weeks earlier under the P2 scenario. Fall (P1 or P2) flows in the Gap reach were slightly lower in early fall before equalizing with the baseline flow, while little difference between flows was observed in the Wapato reach throughout the fall season.

3.2 Discharge-habitat functions

Discharge-habitat functions resulting from the coupling of steady-state flows and habitat criteria were varied, depending on salmonid, life stage and reach (Table 1). The discharge-habitat graphs for each species and life stage, by reach, separated by main stem or side channel, are presented in online supplementary file Figures A1–A16.pdf. In addition, spatially explicit simulations (videos) of velocities and depths over a range of flows are available in two online supplementary files ([Gap_depth.wmv](#); [Wapato_velocity.wmv](#)). Additional online supplementary files (videos) show predicted habitat at various flows and life stages for coho and Chinook salmon in both reaches ([Gap_Coho_Winter_Rearing.wmv](#); [Wapato_Chinook_Spawn.wmv](#); [Wapato_Coho_Summer_Rearing.wmv](#); [Gap_Chinook_Fry_Rearing.wmv](#)). In each video, the low-flow habitat is shown first (~90 % exceedance), followed by successively higher flows, until the maximum is reached (~5 % exceedance).

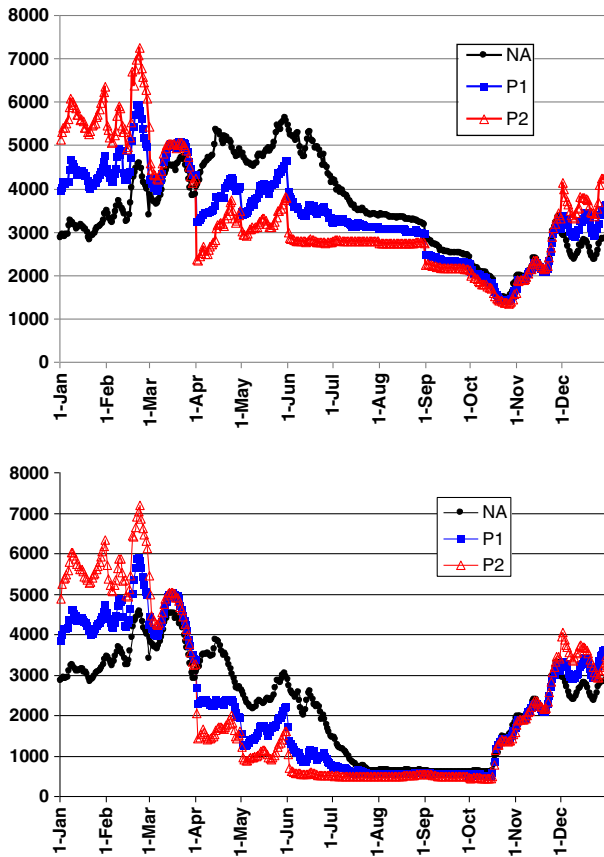


Fig. 2 Three simulated hydrographs in the Gap (*top*) and Wapato (*bottom*) reaches, computed with a river operations model (RiverWare™) under standard operational rules in the Yakima River Basin. For each simulation, a watershed model provided Riverware with unmodified mean daily flows (No Action alternative) that were estimated under baseline climatic conditions (NA) between 1981 and 2005, under a plus 1 °C mean air temperature increase (P1), and under a plus 2 °C mean air temperature increase (P2). The X axis is the date, while the Y axis is discharge (cfs)

Total fall Chinook salmon spawning habitat increased with flow in a nonlinear fashion in the Gap and Wapato reaches (Table 1, Fig. A1) and the shape of the curves indicated a strong geomorphic constraint to habitat formation. When examined separately, side-channel Chinook spawning habitat increased steadily with flow in both reaches, while main-stem habitat showed small (Gap) to large (Wapato) increases at lower flows, before leveling off and then decreasing at the highest flows.

Total spawning habitat for coho salmon varied dramatically in both reaches by flow (Fig. A2), increasing slightly before declining rapidly in the Gap reach, while increasing steadily in the Wapato reach. This pattern suggests a geomorphic constraint (e.g., channel geometry) limited coho salmon spawning habitat in the Gap reach, but not in the Wapato reach. The pattern of response differed in main stem and side channels, where increasing flows produced more coho spawning habitat in side channels, but less in the main stem.

Total fall Chinook or coho salmon rearing habitat (spring or spring/summer, respectively) increased by flow in a linear fashion for both species and reaches (Figs. A3 and A4),

Table 1 Discharge-habitat functions for fall Chinook and coho salmon in the Gap and Wapato reaches. Discharge-habitat functions were obtained in two steps. First, fish habitat was identified and quantified over a range of flows (low to high) using GIS and a rule-based model (e.g., correct water depth, velocity, distance to shore). Second, a regression was fit to flows and habitat with a best-fitting curve routine. Figure and panel (*top* or *bottom*) are located in the Appendix (Figures A1–A14.doc). In each discharge-habitat function listed below, *x* is discharge (cfs) and *y* is predicted habitat (ha) at a given flow

Life stage	Reach	Discharge-habitat function	R ²	Figure
Fall Chinook spawning				
	Gap	$y = -0.00000009x^2 + 0.00115045x + 5.02404$	0.88	A1 top
	Wapato	$y = 9.6677 \ln(x) - 43.677$	0.9581	A2 bottom
Coho spawning				
	Gap	$y = -0.00000003x^2 + 0.00018300x + 3.064125$	0.9121	A2 top
	Wapato	$y = 0.0011x + 13.842$	0.8688	A2 bottom
Coho summer rearing				
	Gap	$y = 0.0009x + 6.8144$	0.9617	A3 top
	Wapato	$y = 0.0035x + 19.37$	0.9659	A3 bottom
Fall Chinook rearing				
	Gap	$y = 0.001x + 8.6972$	0.9503	A4 top
	Wapato	$y = 0.005x + 25.487$	0.9804	A4 bottom
Fall Chinook fry				
	Gap	$y = -0.0002x + 7.86$	0.9772	A5 top
	Wapato	$y = -0.0000001x^2 + 0.0020227x + 18.2701474$	0.6536	A5 bottom
Coho fry				
	Gap	$y = -0.0002x + 7.8262$	0.9727	A6 top
	Wapato	$y = -0.0000001x^2 + 0.0019x + 17.972$	0.6521	A6 bottom
Coho winter rearing				
	Gap	$y = 0.0000001x^2 + 0.0001744x + 16.27845$	0.9623	A7 top
	Wapato	$y = -0.0000004x^2 + 0.0092228x + 26.7200276$	0.9336	A7 bottom

suggesting no geomorphic constraint in habitat formation. However, an important distinction between these two reaches was the rate of habitat response to flow, with the Wapato reach producing much more coho and Chinook spring/summer rearing habitats by flow than the Gap reach (note the differences in slope). In contrast, side channels produced steadily more coho or fall Chinook spring/summer rearing habitats as flow increased in both reaches, while the main stem produced flat responses.

Fry habitat for both species decreased with increasing flows in a linear fashion in the Gap reach, while habitat increased rapidly before leveling out and then decreasing rapidly in the Wapato reach (Figs A5 and A6, respectively). These patterns indicate a strong geomorphic constraint limited the amount of Chinook and coho salmon fry habitat in the Gap reach, while the amount of habitat in the Wapato reach was very responsive to low to moderate flows before leveling out and then descending. The discharge-habitat functions were markedly different in the main stem and side channels, by reach. Specifically, fry habitat formation for both species was unresponsive to flow in the Gap reach, but decreased steadily with flow in the main stem. In contrast, fry habitat for both species increased rapidly with flow in side channels of the Wapato reach before leveling off, while the main stem showed only a slight positive response in habitat formation at lower flows before becoming sharply negative.

Coho winter rearing habitat increased with flow in both reaches, with no upper limit identified in the Gap reach, but a ceiling was evident in the Wapato reach (Fig. A7), suggesting a geomorphic constraint. The discharge-habitat functions were markedly different in the main stem and side channels, with coho rearing habitat increasing with flow in side channels of both reaches, but remaining constant in the main stems.

3.3 Habitat trajectories

The effects of climate change on Yakima River salmonid habitats were mixed depending on reach, species, and life stage (Table 2). Of the 28 discharge-habitat responses we examined, 75 % showed a decrease in habitat quantity and 25 % showed an increase. In all cases, the P2 scenario produced the largest changes in mean daily habitat compared with baseline. Salmonid life-stage specific habitat responses to individual climate scenarios are shown in box-and-whisker plots and line graphs (A7–A15: online supplementary file Figures A1–A16.pdf).

Chinook salmon fry habitat decreased 7–8 % in the two reaches compared with baseline under the P1 scenario, and between 14 and 16 % under P2 (Table 2). In contrast, coho salmon fry habitat decreased 21–32 % under the P1 scenario, and 36–53 % under P2. The median amount of Chinook salmon fry habitat predicted for each climate scenario differed little within each reach, but the spread in quartiles increased dramatically under P1 and P2 scenarios (Fig. A8). The temporal pattern of fall Chinook fry habitat was a mirror image of itself in the Gap and Wapato reaches, where fry habitat decreased between 1 March and 30 April in both reaches under baseline conditions, increased in the Gap reach under future conditions, but decreased in the Wapato reach. Coho salmon fry habitat increased under P1 and P2 scenarios, but decreased in the Wapato reach between 1 April and 31 May (Fig. A9). The future (i.e., P1, P2) habitat daily time series tracked the baseline estimates, with the P1 and P2 producing more coho fry habitat than the baseline in the Gap reach, but less in the Wapato reach.

Fall Chinook salmon spawning habitat decreased 2–4 % in both reaches, with little change observed between climate scenarios (Table 2). The daily habitat time series for fall Chinook salmon spawning habitat was very similar under baseline or future scenarios (Fig. A10). In both reaches, the baseline produced more spawning habitat in the early season, followed by a convergence and then little difference the rest of the season. Spawning habitat for coho salmon increased 10 % in both reaches under the P1 scenario, and increased 17–23 % under P2. The daily spawning habitat time series differed between reaches (Fig. A11). In the first half of the

Table 2 Predicted changes (%) in fall Chinook and coho salmon habitat (four life stages) in two river reaches, under two climate scenarios (P1 or P2), compared with the daily average habitat modeled under baseline conditions (1981–2005). Fourteen discharge-habitat scenarios were examined under two climate scenarios, resulting in twenty-eight possible outcomes

	Coho_P1	Coho_P2	Chinook_P1	Chinook_P2
Gap Spawning	10.71	22.63	-3.19	-3.73
Wapato Spawning	10.58	16.85	-2.40	-1.88
Gap Rearing	-16.35	-27.24	-19.60	-34.54
Wapato Rearing	-37.16	-52.18	-33.83	-56.02
Gap Fry	-20.89	-35.89	-7.17	-14.40
Wapato Fry	-32.29	-53.29	-8.22	-16.23
Gap Winter	-0.45	2.26		
Wapato Winter	10.85	20.98		

season (1 November – 1 December) habitat tracked closely in both reaches, then increased steadily under P1 and P2 scenarios in the Wapato reach, while habitat crossovers occurred in the Gap reach.

Fall Chinook salmon spring rearing habitat declined 20–34 % in the Gap and Wapato reaches under the P1 scenario, and 34–56 % under P2 (Table 2). The spread in the quartiles decreased in the P1 and P2 scenarios, indicating decreased variability in the daily habitat time series (Fig. A12). Coho salmon spring/summer rearing habitat declined in both reaches 16–37 % under the P1 scenario, and 27–52 % under P2. In both reaches the amount of predicted rearing habitat was substantially more under the baseline conditions in early to mid season, followed by a sharp convergence and little difference in late season (Fig. A13).

Coho salmon winter rearing habitat decreased 4.5 % in the Gap reach under the P1 scenario, while increasing 11 % in the Wapato reach (Table 2; Fig. A14). Winter rearing habitat increased 2–21 % in the Gap and Wapato reaches under the P2 scenario, with the Wapato reach showing the greatest sensitivity (Fig. A15). There were very small differences in the median values for overwintering habitat within each reach, but the spread in the data increased in both future scenarios. The daily time series was unique compared to other life stages because the estimates started out similar, diverged, converged, and then crossed over the baseline in late season. In early season (Oct – Nov) there was close agreement between the habitat estimates, but in mid season (Dec – Feb) the future scenarios increased habitat, followed by a substantial decrease (below the baseline) in late March and April, mirroring the underlying hydrographs.

3.4 Sensitivity analysis

A simulated swapping of hydrographs in the Gap and Wapato reaches and a recomputation of habitat resulted in small to large changes depending on reach, species, life stage, or climate scenario (Table 3; Fig. A16). Of the 42 discharge-habitat combinations examined, 67 % showed an increase in habitat and 33 % a negative response. Rearing habitat for both species increased 32–38 % in the Wapato reach, while decreasing 18–23 % in the Gap reach. Fry

Table 3 Changes in simulated salmonid habitats (%) after we simulated swapping (substituting) the hydrographs in the Gap and Wapato reaches, effectively reducing flows in the Gap reach while increasing them in the Wapato reach. A total of 42 discharge-habitat responses were examined for fall Chinook and coho salmon - four life stages (spawning, rearing, fry, winter), two river reaches (Gap or Wapato), and three climate scenarios (No Action [NA]=baseline, P1, or P2)

Reach/life stage	Coho_NA	Coho_P1	Coho_P2	Chinook_NA	Chinook_P1	Chinook_P2
G_W_Spawning ^a	-0.01	-0.01	0.13	-5.67	-5.46	-5.31
W_G_Spawning ^b	0.04	0.07	0.99	13.21	13.78	14.57
G_W_Rearing ^a	-22.60	-22.10	-20.70	-17.96	-18.35	-17.94
W_G_Rearing ^b	38.17	37.66	34.88	32.26	34.46	34.55
G_W_Fry ^a	5.77	5.37	4.92	2.50	2.41	2.29
W_G_Fry ^b	9.86	11.72	12.62	4.33	4.87	5.18
G_W_Winter ^a	-5.41	-3.33	-2.32			
W_G_Winter ^b	15.39	11.51	9.22			

^a Gap reach hydrograph was replaced with Wapato reach hydrograph

^b Wapato reach hydrograph was replaced with Gap reach hydrograph

habitat increased 2–13 % for both species and reaches, with Wapato reach coho habitat appearing most sensitive. Fall Chinook salmon spawning habitat increased in the Wapato reach 13–15 %, while increasing 1 % in the Gap reach. Winter rearing habitat for coho salmon resulted in a 9–15 % gain in the Gap reach, and a 2–5 % loss in the Wapato reach.

4 Discussion

4.1 Habitat trajectories

Of particular concern is the downward projection in fry/rearing habitats for coho and fall Chinook salmon in both reaches. Simulated changes were more extreme for both species under the P2 scenario than P1, and in the Wapato reach where management reduces discharge in spring and summer. A warmer future is expected to produce less water for the Yakima River in the late spring and summer months (Mastin 2008), making the river shallower, less connected to its floodplain, and less suitable for salmonids. One likely response that these rearing-staged fish might have is to move upstream or downstream in search for better habitat. However, upstream movement is impeded by diversion dams, while downstream habitat will be worse due to higher stream temperatures.

Breaking out the main stem from the side channels revealed different patterns in habitat quantity as a response to changes in flow. Of the 14 unique discharge-habitat scenarios we examined in this analysis (Fig. A1–A7), only twice (14 %) did the main stem produce significantly more habitat than side channels (fall Chinook salmon spawning habitat in both reaches). In another three scenarios (21 %), main stems and side channels produced a similar amount of habitat (coho spawning in both reaches, and coho summer rearing (Gap). In the remaining nine reaches (65 %), side channels produced substantially more habitat than the main stem, indicating the importance of hydrologic connectivity to meet life-stage specific habitat needs (Ebersole et al. 2006).

4.2 Sensitivity analysis

Swapping the hydrographs in both reaches increased our understanding of salmonid habitat potential with and without diversion dams. Sixty-seven percent of the 42 discharge-habitat scenarios we examined in this analysis after swapping the hydrographs resulted in increased habitat, while 33 % decreased. Rearing habitat for both species showed large increases in habitat (32–38 %) when we increased flows in the Wapato reach during spring and summer, while moderate losses occurred (18–23 %) in the Gap reach after we decreased discharge. Similar patterns were observed for spawning and winter rearing habitats, where more habitat was achieved for both species after increasing flows in the Wapato reach compared to reduced flows in the Gap reach. The one exception where habitat increased in both reaches for each species was fry habitat, but even in this case the gains in habitat were predicted to be twice as large in the Wapato reach after we simulated increased flows. Thus the habitat gains for each species and life stage achieved through flow augmentation in the Gap reach were negatively offset by the losses in habitat in the Wapato reach due to flow reduction.

4.3 Decision support

The minimum base flow set at the Sunnyside Diversion Dam is determined annually by the amount of water in the Yakima River Basin. Outlined in the Interim Operating Plan for the

Yakima Storage Project (USBR 2002), a balancing act occurs between non-proratable water-right users (those with the most senior rights) and instream flows for fish. High-water years result in larger target (base) flows in the Wapato reach (~17.0 cms) while drier years result in lower base flows (~8.5 cms). The storage control date is the cutoff date when unregulated flows will not be able to supply the minimum flows required under Article XII to support fish habitat unless supplemented with regulated (reservoir release) flows (USBR 2002). Low-water years result in the storage control date being set prior to July 1 while higher-water years result in a later storage control date. The earlier the storage control date is activated, the longer fish will have to survive with minimum base flows. Simulations (Mastin 2008; this publication) indicate this date will come earlier and earlier as the Yakima Basin warms up, resulting in less water being released into the lower Yakima River and a longer and drier summer for salmonids.

A systematic analysis that examines a full range of flows and habitat responses would likely improve our results. Discharge-habitat optimization could form a critical component of a decision support system, enabling managers to visualize changes in a spatially explicit manner with GIS. A decision support system was developed in an earlier study that examined the benefits and tradeoffs between different water-storage scenarios and salmonid habitat in five reaches of the Yakima River (Bovee et al. 2008). A graphically enabled decision support system could simulate hydrographs and habitat time series retrospectively, in real time, or through forecasting. Managers could use decision support to balance the needs of people and fish in the face of a changing climate. Opportunities to do so may arise as agricultural needs shift with climate change or as existing water delivery systems age and need replacement. Our analysis demonstrates that flow augmentation could offset some of the impacts that climate change will have on salmonids in the Yakima Basin.

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