



ESTUARY & SALMON
RESTORATION PROGRAM

Program Report

Summary and synthesis of comments on a study of the “*Biological and Physical Effects of ‘Fish-Friendly’ Tide Gates*”

*WA Department of Fish & Wildlife
Estuary and Salmon Restoration Program
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Photos courtesy of Correigh Green, NOAA. From left to right, 1) reference stream at Lewis and Clark site, 2) SRT at Fisher Slough site and 3) flap gate at North Hanson site.

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SUMMARY

This paper summarizes and translates, into less technical language, a scientific investigation of the biological and physical effects of ‘fish-friendly’ tide gates in the Pacific Northwest. This work was commissioned in 2009 by the Estuary and Salmon Restoration Program (ESRP) and was completed by NOAA’s Fisheries Science Center through an Interagency Agreement ([PRISM Contract 09-1777](#)) with the Recreation and Conservation Office (RCO), acting as ESRP’s fiscal sponsor. The final product of this agreement was a technical report which is provided in its entirety in Appendix B. This investigation was a first step toward a much needed comprehensive evaluation of the effectiveness of tide gates in providing benefits to fish. We expect the results of this study will be of interest to the broader restoration community.

During review and early circulation of this report a number of important questions were raised provoking a useful dialogue about the current state of knowledge and remaining data gaps. Much of this dialogue is preserved in Appendix A as a technical Question and Answer (Q&A) session between authors, reviewers and ESRP staff. We have provided this information to help answer common questions, to clarify some uncertainties presented in the report and to identify priority data gaps need to better inform policy and restoration practice.

Contents of this document:

- Background and context on the tide gate study, including description of the study objectives
- Summary of findings, policy implications and recommendations on future inquiries and applications
- Appendix A: Q & A section in which the study authors address questions about the study design, findings, and interpretation of results. Also included are recommendations on future monitoring and research needs
- Appendix B: The final report on tide gates delivered to ESRP by NOAA as a contract deliverable

APPROACH TO LEARNING

ESRP is accountable for spending limited public funds to advance nearshore restoration and protection in Puget Sound. We recognize there are many uncertainties about restoration practices that affect whether projects deliver maximum intended benefits. Complementing our capital restoration and protection efforts, ESRP has a ‘learning program’ that uses project monitoring and other investigations to produce knowledge useful to the broader restoration community.

ESRP’s learning strategy combines data from: 1) individual projects, 2) rapid ecological assessments and 3) project enhancements to improve our understanding of restoration techniques with the ultimate goal of selecting and managing more cost-effective projects that deliver greater ecological restoration benefits. ESRP identifies key uncertainties that affect project performance and address these uncertainties through targeted investments in project learning.

EVALUATING TIDE GATES AS A RESTORATION TECHNIQUE

The focus of ESRP is to identify and implement nearshore projects that protect and restore the key ecological functions needed to create and sustain the nearshore. To evaluate and select the best projects for funding, ESRP needs to understand the relative value of different types of restoration

actions in providing ecological benefits. Through technical reports developed by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP), including the Management Measures report, we understand the importance of tidal flow for nearshore systems. Tidal flow provides water and sediment routing, fish passage and the delivery of nutrients within the estuary and from one part of the system to another. In many places across Puget Sound, tidal flow is altered by the placement of physical structures such as dams, levees, tide gates, culverts and other man-made structures placed in waterways. Removal or modification of these types of structures is a common element in restoration proposals and are generally referred to as hydraulic modifications. We know there are uncertainties about the relative ecological benefits of different types of hydraulic modifications and trade-offs in terms of costs and benefits.

As a grant program, ESRP encounters project proposals that include tide gates and needs to evaluate their effectiveness as a restoration technique. In some cases, tide gates are simply one element in a larger project, and in other cases tide gates are proposed as the primary restoration action to improve tidal flow and fish passage in an otherwise inaccessible area. While natural channels and breached levees undoubtedly have greater ecological benefits than systems with tide gates, complete removal of tide gates is not always possible. In cases where full restoration or dike breaching is not possible, we need to understand whether tide gates can provide meaningful ecological benefits and how the design and management of tide gates affect their ability to provide ecological benefits. The tide gate study was envisioned by ESRP and NOAA as a first quantitative and comprehensive approach to evaluate the relative benefits of different types of tide gates compared with natural conditions that would be obtained through a dike breach or removal.

STUDY OVERVIEW

The purpose of the tide gate study was to complete a comparative analysis of various tide gates used in estuarine environments in the Pacific Northwest. This study is one of the first attempts to evaluate, across the region, the effectiveness of self-regulating tide gates (SRTs) in restoring tidal flow and improving fish passage. NOAA was tasked with: 1) developing a list of tide gate sites to study, 2) identifying appropriate comparison sites, 3) developing a list of hydrological and biological indicators to monitor, 4) designing a rigorous study design, 5) monitoring individual sites for up to one year and 6) preparing a final publishable report. The project was initiated in 2009 and the final report received and approved in February 2012.

The study design included separate spatial and temporal components. The spatial study evaluated physical and ecological characteristics at ten sites with SRTs and compared these with reference sites and sites with flap gates. Sites were sampled three times during a single season. The temporal study included three sites where flap gates were replaced with SRTs; these sites were evaluated multiple times over a period in which design and operations changed. In both studies, a number of physical and biological effects were evaluated including: connectivity (tidal muting), salinity, temperature, water velocity and frequency and densities of numerous species (estuarine and non-estuarine dependent).

WHAT DOES THIS REPORT TELL US?

The tide gate report presented a number of findings some with greater certainty than others. While there are many nuances to how this set of observations can and should be used, some of the major findings relevant to ESRP and the restoration community are summarized below.

- ❖ **Tide gates limit fish passage and provide less ecological benefits than natural systems**
- ❖ **The effectiveness of self-regulating tide gates varies by species and life history groups**
 - For estuarine-dependent species including juvenile Chinook salmon, natural sites in this study supported densities an order of magnitude greater than the systems with tide gates
 - Non-estuarine dependent species and adult salmonids were less negatively affected by tide gates
- ❖ **Self-regulating tide gates (SRTs) can provide greater ecological benefits than traditional flap gates**
- ❖ **Tide gates, including SRTs, vary considerably in type and amount of benefits provided**
 - The driving factors related to the effectiveness of tide gates in providing ecological benefits are not well documented
 - Although a good first step, the study was not able to evaluate variability in tide gate operations or design variability among SRTs. More information is needed to understand the potential for significantly improving the benefits of SRTs through informed design and operation
- ❖ **Continued studies are needed** to better understand how tide gate design and operation affect physical process and how these changes affect habitat use by estuarine species, especially in the case of SRTs. Until these issues are better understood it will be difficult to evaluate whether SRTs provide significant enough benefits over traditional flap gates to be considered a useful restoration element. We also need to understand the type and amount of habitat potentially made available upstream of any replacement tide gate in order to gauge the value of the installation.

HOW COULD THIS INFORMATION BE USED?

This report is a good foundation for on-going study of the value of tide gates in restoration practice and adds to the growing body of knowledge about the science of estuary restoration. Prior to this report, scientific information was very limited with respect to effects of tide gates on fish passage and habitat use. As the authors indicate, relevant management decisions were being made, largely in the absence of information. This study greatly increased the amount of information about tide gate function and fish use, and it found several strong patterns in terms of connectivity and habitat utilization by juvenile Chinook salmon and estuarine-dependent species. Not unexpectedly, areas upstream of SRTs with comparable habitat conditions had lower rates of fish usage than reference sites. Compared with areas upstream of flap gates, SRTs were similar or had somewhat higher rates of juvenile Chinook utilization. Together these results represent the best available science set forward in NEPA, ESA, and other laws.

ESRP may use this information to:

- ❖ More accurately evaluate the ecological benefits, technical merits and potential limitations of restoration proposals that rely on hydraulic modifications such as dike breaches or tide gate

installation to achieve ecological objectives

- ❖ Provide guidance to ESRP peer reviewers who evaluate and rank ESRP proposals
- ❖ Provide technical guidance to the restoration community with the goal of informing future restoration design to maximize benefits to ecological processes and estuarine species
- ❖ Stimulate discussion within the scientific and restoration community about the trade-offs in advancing restoration actions at sites that cannot restore full function
- ❖ Identify critical information gaps and monitoring needs that can inform future investment decisions about monitoring and program learning

The information generated in the study may also have uses outside of the restoration community for activities such as developing best management practices for tide gates on agricultural or other working lands.

HOW WILL TIDE GATES BE EVALUATED IN GRANT PROPOSALS?

ESRP will consider information presented in this study when evaluating proposals where the ecological outcome of a project is largely dependent upon benefits provided by installation of a tide gate.

Knowing that SRTs do not provide the same benefits as unobstructed channels, project proponents will need to demonstrate to ESRP the habitat benefit gained at a particular installation from an SRT compared with a dike breach or removal. Hydraulic modeling of operational connectivity would be one way to evaluate the value of an SRT in terms of providing tidal flow, but may not be an effective way to understand how fish passage or other parameters would be affected by a tide gate. If a proposed project design includes a tide gate when breach or removing a levee is possible, it will likely receive low marks on technical merit. Similarly, if the tide gate design and/or operations and management will result in the gate being closed during time periods important for fish, it also is likely to receive lower scores for technical merit compared with a proposal that has a dike breach, removal or set-back and allows unimpeded fish passage.

It should be noted, however that there are times when a tide gate is included in a proposal but does not significantly affect the intended ecological benefits of the project. Project proposals may include elements that provide value other than ecological benefits such as public access and recreation, safety, environmental education or to encourage social feasibility. An example of a project where a tide gate is included but doesn't significantly affect the ecological outcomes might be a dike setback in which a tide gate is installed on the new landward edge and is included to improve social acceptability of the project to adjacent landowners. In this case, the ecological benefits are achieved primarily by the dike setback itself and the inclusion of a tide gate should not significantly affect the technical or ecological merit of the project.

UNANSWERED QUESTIONS AND RECOMMENDATIONS

This study is a good first step in critically evaluating and collecting data on the effects of tide gates on juvenile Chinook and other species and the potential benefits of alternative tide gate designs, such as SRTs, in restoration projects. Due to the limited evaluation period and number of gates sampled, particularly in the temporal study, a number of questions remain unanswered and new questions

generated. There remains enough uncertainty about some issues raised by the study that broad conclusions or suggested new SRT policies related to regional recovery goals would be premature at this time. There also remain a number of broad questions that affect our ability to fully understand the benefits and costs of various types of estuary restoration efforts (e.g. *“how do juvenile Chinook salmon respond to various types of estuary restoration?”*; *“how are salinity, moisture and drainage affected by SRT design and operation?”* or *“how do vegetation communities (riparian environments, wetland plants) respond to design and operation of SRTs and other restoration designs?”*). The section below summarizes some of the unanswered questions and includes recommendations from the authors on designing future studies to help answer these questions and provide more guidance for decision-making. More details and recommendations are provided by the study authors in Appendix B.

Tide gate design and operations - The report and questions received by ESRP clearly identifies the need to better understand the extent to which the design, operations and maintenance of SRTs can increase ecological benefits to juvenile Chinook and other species. Results of this and future studies could be used to calibrate a hydraulic model to provide insight into how operations and maintenance of SRTs could affect the value of tide gates.

- ❖ Do different styles of SRTs provide more benefits than others and why?
- ❖ Is there value in replacing flap gates with SRTs? Can tide gate operation affect ecological benefits?
- ❖ What operational actions would allow a tide gate to provide more ecological benefits?
- ❖ How much benefit can be gained through operational or design changes?
- ❖ What monitoring can be done to allow for adaptive management of gate operations to improve function?

A number of recommendations were made by the authors in the Q&A section related to tide gate design and operations. A longer term experimental study of several tide gate sites of varied designs could test how much influence operation can have over ecological responses like fish habitat use. In particular, an experimental station that allowed various design criteria (e.g., door opening size, opening angle, pet doors) to be tested in the field would be extremely useful for determining critical design features for supporting rearing by Chinook salmon. This type of station could improve our ability to develop fish-friendly design features much more quickly than piece-meal additions by various restoration projects added over many years.

Recommendations on evaluation of tide gate performance included at least two years of before and after project implementation monitoring for new sites, preferably in association with a reference site and with inclusion of biotic and abiotic indicators (e.g. temperature, salinity, and water level loggers up- and downstream of SRTs). Monitoring fish both above and below tide gates multiple times during the season (biweekly sampling is ideal) was highly recommended.

The study authors also suggested a score card approach to evaluating the effectiveness of tide gates in providing fish passage. Such an approach would be based on the upstream/downstream fish density ratio (see Appendix A- Q8 for additional details).

Guidance on tide gate operations to benefit juvenile salmon

- ❖ Maximize gate opening width and time to improve “openness” which generally leads to greater connectivity for fish. Side-hinged gates tend to do this better than flap gates
- ❖ Maximize culvert width or number of culverts. The ratio of Chinook salmon densities above to below tide gates increased as a function of the channel width that is potentially open. Larger culverts should also reduce velocity inside culverts.
- ❖ Minimize the height of the culvert invert. Keeping the culvert low in the channel provided deeper water in the culvert and prevents plunges from forming during ebb tides.
- ❖ Increase depth of water upstream of tide gate at high tide. Chinook salmon prefer rearing in channels that are 1-2 meters deep. Clearly, there is a trade-off of water depth with drainage; and tide gates are designed to limit upstream water depth, so this guideline will depend upon local site characteristics.

APPENDIX A

TECHNICAL QUESTIONS AND ANSWERS (Q&A)

This section summarizes comments and questions received by ESRP during early review of the final tide gate report to ESRP. We found this dialogue to be particularly useful in understanding the complexities involved in assessing the effectiveness of tide gates and in understanding the current state of knowledge. This section is intended to stimulate discussion around the technical uncertainties associated with the report, to provide clarifying information about the study itself and to assemble recommendations on future priority data gaps that could be addressed through additional research. This appendix organizes comments and questions into topic areas and below each question, responses from the authors or other experts are provided. Recommendations on strategies for addressing the critical data gaps are summarized by topic.

Comments and monitoring recommendations were provided by the Washington Department of Fish and Wildlife; Conservation Districts of San Juan Islands, Skagit, Whatcom, and Whidbey Island; NOAA's Restoration Center, The Nature Conservancy and Skagit Watershed Council. Responses to technical questions and recommendations on future recommendations were provided by authors of the tide gate report (Greene and Beamer) and other experts.

Site Specific

Q1 The study equates “before project” tide gates at the Fisher Slough site, which allowed unrestricted upstream access during the part of the year when they were tied open, with conventional flap gates, which open only to drain high water. The study also only sampled at Fisher Slough upstream of the new SRTs during two years when they were closed all summer. How might these factors have affected the Chinook densities that were measured?

Response: The report states that gate type, design, and operation have a strong influence on ecological results. However, the passive gate at Fisher Slough was not equated with flap gates. Figure 12 explicitly identifies passive side-hinge and passive flap gates; the discussion emphasizes the important elements of both their operation and design. Future fish results at the Fisher Slough site will likely improve when normal gate operations recommence.

Recommended future study: Continued monitoring at Fisher Slough through at least several years of normal gate operation, including fish, environment, and gate operational variables.

Q2 Fisher SRT appears to be an exception to the general hypothesis that increasing connectivity results in increased Chinook passage and function. The Fisher SRT increased connectivity by some metrics and held other metrics essentially unchanged, and yet Chinook passage plummeted by 7-fold or more. The report concludes that varying operations were responsible, but this might reasonably account for only a small portion of the drop. Could other factors be contributing to this result such as increased ground vibrations associated with restoration upstream of the gates? Heavy equipment was operated daily starting in April and continuing through the fish migration. What might be some of the reasons for this exception?

Response: Potential factors such as the active restoration project upstream of the gate were not measured. Some studies (see Feist 1991) have shown that noise disturbance at can result in fish (including juvenile salmon) mortality and avoidance of “noisy areas. It would be possible to test whether noise disturbance was a potential cause of the negative results at Fisher Slough during the construction years (2010 and 2011) by pairing Chinook density result by date if we knew when heavy equipment use occurred at the site. However, monthly results from 2010 do not show any change in the up/downstream pattern of Chinook density (Beamer et al 2011, Figure 16).

Another possible explanation is differences in overall juvenile Chinook population size within the Skagit estuary. Years with many fish in the estuary may result in higher densities in upstream habitats through density dependent pressure. As habitat fills up with fish in higher population years, more fish may colonize habitat available further upstream in channel systems such as Fisher Slough. However, we do not believe that interannual differences in juvenile Chinook population size in the Skagit estuary are the cause of negative results at Fisher for two reasons. First, the Chinook ratio result method was designed to be robust against this external factor by using fish density results upstream and downstream in the local vicinity of the site. The figure below (top panel) shows that Chinook ratio does not vary with population size. Also shown in the figure below (bottom panel), results at Fisher Slough are not supported by the idea that Chinook population size in the Skagit estuary is the cause of negative results. The year before floodgate replacement (2009) had a wild juvenile Chinook outmigration population size of 2.8 million. In 2010 and 2011, the outmigration sizes were 1.6 and 3.7 million, respectively. If overall

juvenile Chinook population size was influencing Fisher results, then we’d expect more fish in 2011 than in 2009 or 2010.

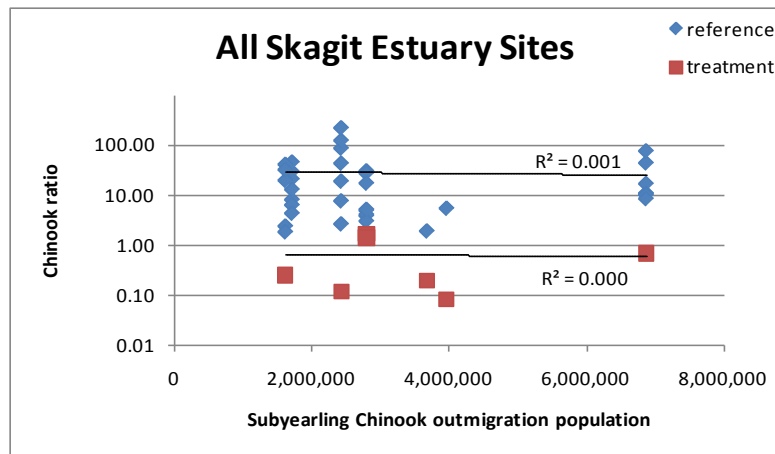
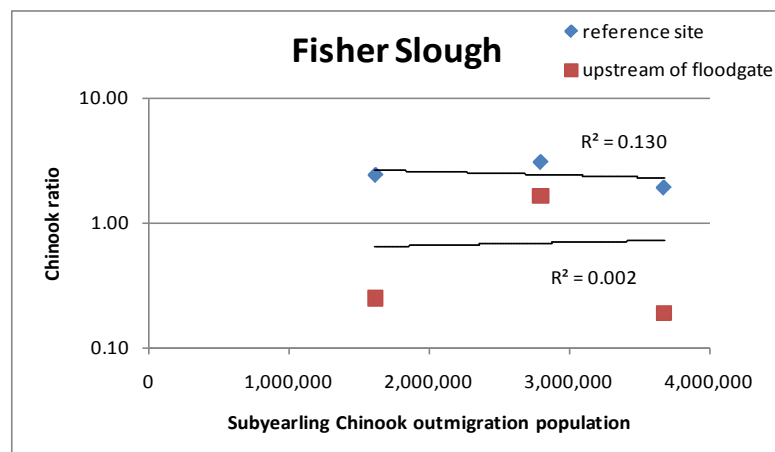


Figure Q2. Relationship between seasonal juvenile Chinook ratio and subyearling Chinook outmigration population size. Population size estimates are made by WDFW using catch data collected at a mainstem trap located in the Skagit River near Burlington, WA.



Recommended future study: Continued monitoring of Fisher Slough, especially now that “normal” gate operation can commence. However, a restoration treatment effect (new habitat available to fish as a result of dike setback) may now confound our ability to ever know the causes of negative results at Fisher Slough for the two years following floodgate removal.

Q3 The Fisher site appears to be different in several respects from other sites, including culvert opening size, area of gated channel and position in system (invert elevation relative to MLW). Are there any ideas as to why the old style passive/manual tide gate at Fisher was far better for Chinook passage than all other gates, both flap and SRT? Cumulative density ratios at the old Fisher gate (1.62) were about 66% of Fisher's reference site (2.46), while other tide gates and SRTs had density ratios ranging from 0.12 to 0.66 (1-12% of reference sites). At one point the report suggests that, given its level of connectivity, we would expect the new Fisher SRT "under normal operation" to perform better than the other SRTs. Certainly if it performs as expected, better than the old gate it replaced, than the Fisher site will be operating at a far higher level of function than other tide gate sites. Since a primary objective of the report is to describe how SRTs affect function for Chinook, it would be very helpful to have a discussion about why the Fisher gate has the potential to function so much better than others. What are the characteristics that made the old gate, and likely will make the new gate, function at a relatively high level?

Response: Learning much more about the old gate is not possible because there was only one year of monitoring completed before the old gate was replaced. Gate operation varied between years and was not operated "normally" after the old gate was replaced because of restoration occurring at the site. This will not be the case in future years. The report states that gate operational differences between years are a possible cause of the disappointing fish response after floodgate replacement at Fisher Slough. Also, factors other than gate operation at Fisher Slough related to the structure's design – such as the overall gate opening sizes and their door type (side hinge) – are not very different. The Fisher gate has the potential to work better than other SRT sites because of its ability to be operated with a high level of connectivity and it has such large opening size compared to the overall channel width. Our report showed overall that these variables are strongly correlated with Chinook results.

Recommended future study: Post-restoration construction monitoring is needed at the Fisher Slough site to complete the comparison with the other two sites in the temporally extensive study. Monitoring of the designed vs. actual operation of the SRTs (are they operating as designed) would be useful.

Q4 Reference sites seem to be more similar to the river than Fisher Slough (and possibly other study sites). Fisher Slough is not located on the main stem of the river which is unlike the location of the reference site. Isn't the placement or connectivity of the sample sites compared to that of the reference site location relevant to the results?

Response: Representativeness of reference sites is an important issue. However, any study is constrained by the channels present within the landscape for reference site selection. With respect to Fisher Slough, the reference site is located adjacent to the floodgate so its landscape connectivity value is essentially identical to the floodgate. It is true that the reference channel is different in size (smaller than Fisher Slough) and its freshwater hydrological nature (does not have tributary watershed upstream). However, tidal hydrological influences are identical to the floodgate sites. Overall, we do not believe reference site selection at Fisher Slough is a serious flaw in the study design.

Additionally, specific defects in individually paired reference sites are somewhat offset by including the additional reference site results from natural channels throughout the Skagit estuary which does include at least one additional tidal freshwater system. The report shows a consistent result for all natural channel reference sites – juvenile Chinook ratio results are always greater than 1.8 (and usually much

higher) which is a dramatic difference for the same result measured at passive gate or SRT sites, except for Fisher (1.62) and S. Fornsby (1.38), both in 2009.

Recommended future study: Longer term study of several tide gate sites of varied designs where their operation is experimental varied to test how much influence operation can have over ecological response, such as fish results. See elaboration in Q7 (Tide gate O & M section).

Q5 One of the tentative conclusions is that various operations that reduce connectivity and mute tidal elevation result in a fraction of the seasonal rearing for Chinook salmon; however for the Fisher example the overall connectivity increased yet there was still a decrease in Chinook densities. What are the other potential confounding factors that may have influenced these results including closing of the flood gates for construction and impacts from those construction activities to the system? The report by Eric Beamer is cited, but additional explanations would strengthen the results of this study and interpretations of the results.

Response: *There are numerous possible explanations for why Fisher Slough SRT did not respond in the expected direction. 1) The observed patterns are spurious, i.e. occurred by chance. Because there are only three years of data (and only one year of pre-installation data), there is a low probability (<0.1%) that the relatively high densities of fish occurring upstream of the SRT in the first year and the lower densities upstream after restoration is due to chance fluctuations in juvenile Chinook salmon numbers (Beamer et al. 2011); 2) the patterns are not due to chance but are the result of other mechanisms unrelated to restoration. A hypothetical example would be that a pair of kingfishers set up residence upstream of the tide gate after installation, dining on Chinook salmon locally and thereby lowering their density upstream of the tide gate compared to downstream and compared to the reference site; 3) the difference among years is due to changes related to the restoration but not to the installation of the tide gate per se. For example, the channel restoration upstream of the tide gate may have altered turbidity or other water quality parameters, leading to lower juvenile Chinook salmon densities after the tide gate was installed. As noted in the report, this possibility seems unlikely because most restoration activities occurred when few fish naturally rear in the Skagit delta; and 4) differences in fish density might have been due to aspects of connectivity related to the tide gate which were difficult to measure. Operational problems are suspected related to the limited angle the gates opened, and this potential problem may have reduced connectivity.*

Recommended future study: Fisher Slough should be monitored for additional years, preferably more than one year after all restoration has been completed. Additional monitoring should help rule out some of the possibilities listed above. Moreover, if the pattern observed is due to tide gate function, the most likely reason is due to lower connectivity from the doors not opening fully. Better data on door opening angles would help get at this possibility.

Tide gate O&M

Q6 Two temporal study sites, at the South Fornsby Slough and McElroy Slough projects, evaluated the effects of two older-style, Aberdeen-type SRTs, both of which have had operational problems related to the degree to which they open under low stream flow conditions, and both of which provide access to upstream channels that currently have fairly poor habitat quality. How might the operational and habitat quality deficiencies have contributed the low density of juvenile Chinook in the upstream samples? Did/how did the study methodology test for these factors?

Response:

Operational influences - Annual operational differences were accounted for by year at South Fornsby by assigning gate and operation types: manual/passive, passive flap, and SRT (Figure 11). At McElroy, there were not differences between years for this type of assignment. All sampling occurred after tide gate replacement so the study did not measure variability in operation for each assigned type and site combination. For example, direct measurements of tide gate door openness each year and operational type at a site would help sort out effects of operation on juvenile Chinook results. In any case, the results do suggest that Aberdeen-type gates can be a significant improvement over passively operated gates. The average increase in the ratio of cumulative Chinook salmon density at South Fornsby was a 6-fold improvement (Figure 11, Panel B). The best year at South Fornsby when operated as a SRT was a ratio of cumulative Chinook salmon density in 2009 at 1.38 which is almost a 14-fold improvement over the results when the gate was operated as a passive flap.

Local habitat condition influences - Differences in habitat condition at the local level might influence juvenile Chinook salmon densities at sites upstream and downstream of tide gates independent of how the tide gate operates for fish passage. The spatially extensive study shows habitat variables (Figure 8) have less of an effect on Chinook salmon (Figure 9) than site type (flap, SRT, reference). All three temporally extensive study sites were also part of the spatially extensive study where habitat conditions for temperature, salinity, and water level were analyzed, thus analysis of habitat quality is already part of our overall tide gate analysis. It can be difficult to distinguish how much difference in habitat quality is caused by the tide gate's operation and how much might be caused by local conditions not linked to the tide gate (e.g., lack of riparian vegetation in channel upstream which may mediate high water temperature influences).

In addition to analyses completed in the spatially extensive study, habitat condition results at each study site (up and downstream of the tide gate) were compared to known or hypothesized relationships for juvenile Chinook salmon preference or presence in order to determine whether site level habitat conditions during monitoring were influencing juvenile Chinook salmon results independent of the tide gate. The habitat condition relationships for juvenile Chinook salmon are summarized below after analyses used at Fisher Slough and described in Beamer et al. (2010) and (2011). Habitat condition results for the two questioned temporal extensive study sites are shown in Table Q7 below.

- ❖ Minimum water depth threshold for juvenile Chinook salmon presence is 0.20 meters
- ❖ Maximum water velocity threshold for juvenile Chinook salmon presence is 0.38 meters per second.
- ❖ Assume young of the year Chinook salmon are sensitive to salinity stress and will seek low salinity microhabitats to reduce stress and acclimate. Salinity stress may not occur until salinity exceeds 4.5 ppt.
- ❖ Water temperature in excess of 15 degrees C is postulated as stressful to juvenile Chinook salmon in estuaries.
- ❖ Water quality standard in Washington State for dissolved oxygen in freshwater bodies with salmonid rearing and migration is 6.5 mg/l or higher. The 6.5 mg/l level is the mid-point between excellent (6.0) and extraordinary (7.0) water quality designations for marine waters in Washington State.

McElroy Slough local habitat conditions - There is not compelling evidence that habitat conditions upstream of the McElroy tide gate were worse than habitat conditions downstream for juvenile Chinook

salmon rearing during the times monitored. In fact, the reverse appears to be the case. All habitat conditions parameters in the table below at McElroy are better upstream than downstream (Table Q7).

South Fornsby Slough local habitat conditions - Habitat conditions alone are enough to explain the 6.6-fold difference in juvenile Chinook use between SRT verses passive operated tide gate or the 8.3-fold difference between SRT operation and the reference site. Water depth and velocity are likely not adversely influencing juvenile Chinook salmon either up or downstream of the tide gate (Table Q7). However, salinity was nearly always higher than what is considered preferred by Chinook fry at South Fornsby regardless if sites were reference or treatment, up or downstream of the tide gate, or whether the tide gate operated passively or as a SRT. Salinity averaged just over 17 ppt upstream of the tide gate but was lower than salinity downstream of the tide gate on average by 2.3 ppt in years when the tide gate was operated as a SRT and 3.8 ppt when operated passively. Average salinity at the tide gate site was 1.3 ppt lower than salinity at its reference site. Likely, salinity levels in habitat upstream of the tide gate would be slightly more preferable to Chinook in the vicinity of South Fornsby than habitat downstream of the tide gate (i.e., in the very saline Swinomish Channel). While temperature and DO has potential to adversely influence juvenile Chinook abundance, it is estimated to only influence 20% of the juvenile Chinook abundance curve in late spring and summer each year.

Temperature was lower downstream of the tide gate on average by 1.8 degrees C in all years whether the tide gate was operated as a SRT or passively. Temperature started exceeding the juvenile Chinook threshold for stressful at some sites in most years by late May or June. The same pattern was observed for DO at the tide gate site but not the reference site. Only during this later time period would we expect habitat conditions upstream of the Fornsby tide gate to have the potential to lower the number of juvenile Chinook observed in our monitoring. Since it is only a portion (20%) of the total number of juvenile Chinook using the South Fornsby area, we do not believe habitat conditions alone are enough to explain the 6.6-fold difference in juvenile Chinook use between SRT verses passive operated tide gate or the 8.3-fold difference between SRT operation and the reference site.

Table Q6. Percent of time a habitat parameter was exceeded at sites monitored for juvenile Chinook salmon upstream and downstream of tide gates or mouth of reference channel. NC means data were not collected for these years.

Habitat parameter	S. Fornsby Sl. Reference, all years		S. Fornsby Sl., passive operated years		S. Fornsby Sl., SRT operated years		McElroy Sl., all SRT years	
	Upstrm	Dnstrm	Upstrm	Dnstrm	Upstrm	Dnstrm	Upstrm	Dnstrm
Depth	0	0	0	0	0	0	0	0
Velocity	0	1	0	3	0	1	0	5
Salinity	99	100	100	100	96	100	20	71
Temperature	8	17	34	2	34	16	14	41
Dissolved Oxygen	0	0	NC	NC	21	0	10	0

Recommended future study: A longer term study of several tide gate sites and experimentally vary their operation to test how much influence operation can have over fish results. This study should directly measure: 1) operational variables of the tide gate, 2) environmental conditions up and downstream of the tide gate, and 3) fish assemblage up and downstream of the tide gate. The monitoring period each year should encompass the season of use for fish species which are targets for fish passage at the site. For example, Puget Sound sites targeting juvenile Chinook salmon should monitor from February

through August each year. Also, sites should be selected with varied tide gate designs (with replication, if possible) to determine whether specific designs are more “fish friendly.” To control effects of other factors influencing fish, sites selected should not have other treatment effects occurring during this study – such as upstream restoration. To account for variability in targeted fish populations, such as juvenile Chinook salmon, it would be useful to select sites within estuaries of river systems that have juvenile salmon outmigrant monitoring in place.

Q7 How do different gate designs and operating conditions affect gate function? This question is explored to a limited extent in the paper and it seems that it could be discussed in greater detail given the large variability found in design, operations and the resulting performance indicators. There appears to be enough information to at least pull out a number of design and site characteristics that could be studied in greater detail by future researchers at those sites. In addition these observations might inform adaptive management experiments at existing sites.

Response: While there was not enough opportunity to quantitatively address variation in tide gate design and operation, several generalities can be extracted from the study. Following from the idea that vertical, horizontal, and temporal variation in connectivity can greatly influence utilization by fish, our study supports several general design/operational considerations:

- 1) Maximize gate opening width and time. Comparison of passive flap and side hinged gates with SRTs, and analysis of the percentage of time these gates are open, supported the intuitive idea that greater degree of “openness” leads to greater connectivity for fish. Side-hinged gates tend to do this better than flap gates.*
- 2) Maximize culvert width or number of culverts. The ratio of Chinook salmon densities above to below tide gates increased as a function of the channel width that is potentially open. Larger culverts should also reduce velocity inside culverts.*
- 3) Minimize the height of the culvert invert. Keeping the culvert low in the channel provided deeper water in the culvert and prevents plunges from forming during ebb tides.*
- 4) Increase depth of water upstream of tide gate at high tide. Chinook salmon prefer rearing in channels that are 1-2 meters deep. Clearly, there is a trade-off of water depth with drainage; and tide gates are designed to limit upstream water depth, so this guideline will depend upon local site characteristics.*
- 5) Design and operation should be adjustable. If limitations are discovered in the current design, it is prudent to have a design that can be adjusted to improve connectivity if more is necessary.*

Recommended future study: Of the five considerations above, the gate opening angle has the least amount of scientific support. This uncertainty could be addressed with experiments using marked fish and varying the angle of opening on SRTs.

Q8 What additional guidance can you provide for monitoring tide gate performance? The report touches on this in one paragraph, but given the number of projects recently completed, in progress and likely to come in the future, greater detail on monitoring recommendations as well as adaptive management triggers and responses would be very valuable. For example, what lessons can we learn from the complicated outcomes at Fisher Slough. The results seem counter intuitive although we know not all aspects of the project were completed.

Response: For new projects monitoring plans that include at least two years before and after project implementation are recommended, and preferably a reference site for documenting background variation. For abiotic indicators, temperature, salinity, and water level loggers up- and downstream of SRTs will provide a wealth of information, and additional aspects of connectivity should be measured by adding multiple velocity measurements in the culvert, and angle loggers to examine the time and angle at which gates open. Monitoring fish both above and below tide gates multiple times during the season (biweekly sampling is ideal) is highly recommended.

The study indicates that a minimum threshold for adaptive management could occur when juvenile Chinook salmon densities upstream of tide gates are equal to downstream sites (upstream/downstream ratio = 1). At the reference sites representing natural conditions, the upstream/downstream ratio was much greater than 1 (range is 1.9-8.5 for S. Fornsby Slough, 1.9-3.0 for Fisher Slough) meaning that at these sites there are more fish upstream than downstream. If the numbers of juvenile Chinook upstream drop below the number downstream, it may indicate the fish are avoiding upstream areas), so an adaptive management “score card” for the upstream downstream ratio might look like:

- <1. High certainty that SRT is not performing well. Modify operation.*
- 1-2. SRT may be performing adequately. Improve operation if possible.*
- >2. High certainty that SRT is performing well.*

Q9 It appears from the data that there is so much variation at a site and operational level between tide gates that further investigation along these same lines would only support this conclusion. Recognizing how difficult it may have been to find and secure study sites, could future investigation focus on establishing design criteria for maximizing fish benefit that could be applied to site-specific SRT installations? This would be most useful for understanding costs and benefits of proposed projects.

Response: The study highlighted extensive variability, particularly in traditional flap gates. Future studies of additional tide gates can help reduce some of this variation, but at this point experimental approaches are more likely to produce useful information. An experimental station that allowed various design criteria (e.g., door opening size, opening angle, pet doors) to be tested in the field would be extremely useful for determining critical design features for supporting rearing by Chinook salmon. This type of station could improve our knowledge of fish-friendly design features much more quickly than piece-meal additions by various restoration projects added over many years.

Recommended future study: Opportunities to support this type of experimental resource should be encouraged among engineers that produce tide gates, stakeholders interested in using such designs, and biologists.

Sample Size and Site Selection

Q10 Given the difficulty of identifying “reference” sites that have geomorphic and ecologic conditions that are equivalent to the “treatment” sites how was this study able to distinguish the effect of an SRT on upstream Chinook utilization from the effect of general ecological degradation resulting from decades of channel isolation? Simply by virtue of being isolated for decades by flap gates, the habitat conditions at the treatment sites are poorer than at the reference sites and therefore probably less attractive for Chinook salmon.

Response: This issue was examined in the analysis (see Q1). Habitat conditions above SRT sites can be degraded due to a long history of agricultural or other use, confounding some of the study result. The results suggest some moderate degradation (e.g., temperature differences), but the primary differences above and below appear due to variations in tidal flux, which are by design controlled by tide gate connectivity. Our fish densities point to a broad class of fish (estuarine-dependent fish) affected by SRTs, which includes species like sculpin that are pretty resilient to habitat quality impairments.

Most of the reference sites share the same long history of habitat modification as the SRT sites due to the long history of agriculture in the Pacific Northwest. It is extremely difficult to find true estuarine reference sites in the Pacific Northwest. The reference sites in North Puget Sound include a channel that is blocked by flap gates further upstream, a tidal channel whose drainage area had been filled and extensively developed within several hundred yards upstream, and a blind channel within the footprint of a railroad grade. Farther south, our reference sites included an inlet blocked by a road grade just upstream, and a site that had recently undergone restoration (dike removal and channel reconfiguring). The common theme of these reference sites is higher connectivity, not habitat quality.

Recommended future study: Because tide gates by design mute tidal flux and thereby affect upstream habitat quality, disentangling habitat quality and connectivity impairments will likely be a challenge for future studies. Several studies might be able to address this issue:

- 1) Compare functionality of SRTs with recent dike breaches, which are more like unimpeded reference channels, but would share with SRTs a history of upstream habitat quality impairments.
- 2) Perform mark-recapture studies of juvenile salmon. Some of this work is being done at Fornsby Slough by PIT tagging juvenile Chinook salmon, and it could be expanded. It has also been done with juvenile Coho in Southern Oregon (Bass 2010). Both studies have revealed that SRTs appear to limit movements to areas upstream of tide gates. Another way to study this question in the systems of North Puget Sound would be by transplanting dye-marked groups to upstream and downstream areas of tide gates and examining how quickly they move. Downstream to upstream rates could provide an index of connectivity constraints, while upstream to downstream rates could provide an indication of habitat quality issues.

Q11 Over the past several years, a number of newer “muted tidal regulated” (MTR) SRT projects have been completed in the Columbia Estuary, Coos Bay and Humboldt Bay. Monitoring data for some of these projects have already been collected, and even though the projects target different Chinook salmon stocks, it would be worthwhile to evaluate whether the data may have relevance to Puget Sound recovery goals. Would it be useful and possible to expand the sampling size to study some of these over the past several years?

Response: Yes, it would be useful to expand the sample size for a meta-analysis of tide gate function. The study team looked into the potential utility of working with researchers in Coos Bay but it wasn’t possible to expand the project that far south.

Recommended future study: Inclusion of additional sites in a meta-analysis is warranted if the same data are being sampled at other sites in the same way. For example, sites should be monitored both above and below tide gates when gates are closed. It is extremely difficult to apply data from multiple monitoring programs if the methodologies are not similar. Hence, organizations responsible for funding restoration could provide guidelines for monitoring based on this and other studies.

Q12 In Figure 11, Figures A, B, and C did not have the same linear scale for comparison and Figure B was log-transformed. What is the rationale for having different linear scales? Is there a reason why results for 2006, in Figure B, are out of sequence?

Response: The differences in the scale of the y-axis highlight the huge differences in the ratio of upstream and downstream juvenile Chinook densities among study sites and design changes. Hence, we used log-transformation to ease visual comparison among tide gate and reference sites. Similarly, 2006 is out of sequence in Figure B to better visualize differences in design and operation at Fornsby. These changes (and not the particular year) were the key to understanding the constraints of tide gate function at Fornsby Slough.

Q13 Did the Skagit River reference sites (Figure 5) have similar “landscape connectivity” values as the temporally extensive study sites? If not, explain the usefulness of their fish results in comparison to the treatment sites.

Response: Some of the temporally extensive study sites (S. Fornsby and Fisher Slough) had reference sites with nearly equal landscape connectivity. McElroy did not have a reference site. The six additional reference sites provide context for the natural range exhibited in the tidal delta.

The study used upstream/downstream ratio of juvenile Chinook density which provides upstream site data with the appropriate correction to control for connectivity differences at a landscape scale (see Beamer et al. 2005 Appendix D) because both upstream and downstream sites at reference locations have very similar landscape connectivity. Indeed, the upstream/downstream ratio does not strongly correlate with connectivity ($r = 0.187$). Thus, the Chinook ratio result method is robust against influences of landscape connectivity.

Applicability to Restoration & Drainage Management

Q14 SRTs are one tool, among others, that can be used during restoration when it is unfeasible to implement a full scale, levee removal-type nearshore restoration design. Limitations in the study design include limited sample size; variability in operations and maintenance within and between sites. The study implies that even with improved operations and maintenance SRTs will have little value in restoring true connectivity to rearing habitat for Chinook salmon. If additional data were available to conclusively demonstrate that even with improvements to design, operations and maintenance, SRTs provide little benefit compared with natural conditions and marginal benefit over traditional gates, then restoration practitioners and funders should be reluctant to consider them for restoration project designs. What future supplemental studies do you suggest to demonstrate whether there can be adequate benefits from well-managed SRTs?

Response: Despite some limitations based on variability in operation and design among both flap and SRT sites and the limited ability to sample a large number of sites given the time and the budget, strong differences were nonetheless detected between reference and SRT sites. In the spatially extensive study, there was no statistical difference in juvenile Chinook salmon densities between flap and SRTs, but the temporal extensive study at S. Fornsby detected both a strong change from flap to side-hinged SRT, as well as a very strong difference of these treatments with the reference site. Additional data may help to determine in a spatially extensive context whether SRTs perform better than flap gates, but they are unlikely to change the conclusion that SRTs do not perform as well as reference sites. SRTs appear marginally effective in restoring full connectivity. Regardless of limitations, this study does provide

knowledge about the functionality of tide gates that we did not have previously, and in this respect is an important contribution for managers and stakeholders.

What this study does not tell is how effective SRTs could be. There are two larger questions here: 1) how much can tide gate functionality be influenced by design or operation, and 2) what are the benefits relative to costs of SRT installation compared to other estuary restoration techniques. These assessments would provide extremely practical information on whether SRTs can be adaptively managed to restore Chinook salmon habitat for the economic cost (in terms of both restoration and any costs to users upstream of a potential SRT site), and relative to other potential estuary restoration techniques (e.g., dike setback or removal, dike breaching, fill removal, riparian planting).

Recommended future study: ESRP and other entities should look for opportunities to implement an experimental tide gate station (see above). This could be designed in the context of a site slated for a typical tide gate installation, assuming land owners were supportive. A study comparing different types of estuary restoration techniques that includes SRTs is also recommended.

Q15 In situations where dike removal is not possible, when is replacing an old passive gate with a SRT worth the cost in terms of Chinook benefit? This paper appropriately demonstrates that dike setback or removal is likely to result in far more Chinook benefit than replacing a flap gate with a SRT. But flap gate replacement is often considered in places where dike removal is not possible. In these cases, how should stakeholders determine whether to replace an old gate with an SRT? The discussion section implies that SRTs provide little function for Chinook, which might lead a drainage advocate to argue that replacing an old gate with a SRT isn't worth the added cost. The Fisher Slough example, where density ratios far exceeding other sites are expected even though Fisher's upstream tidal limit was less than half that of some sites in the report, demonstrates that there are likely to be places where substantial improvements might be achieved.

Response: *Three dimensions of rearing habitat are worth considering when determining whether stakeholders might advocate for an SRT replacement: 1) connectivity, 2) maximum possible production (also called capacity, which is the maximum fish density multiplied by habitat area), and 3) habitat quality. As shown in the hypothetical graph below, increasing both habitat quality and connectivity will increase maximum production a given site can support through changes in maximum density. In addition, large areas will also support a higher maximum production. On the graph is shown the connectivity of flap, SRTs, and reference sites as dashed vertical lines (lines with arrows denote variation). Stakeholders interested in improving maximum production should focus on sites with high habitat quality, but thereafter, the choice of what restoration to do could depend on the area of habitat restored. As noted by the black dots, replacement of a flap gate draining a large channel system with a well-connected SRT could result in the same maximum production as restoration to reference conditions (e.g., dike removal) at a small site. Of course, this graph is highly conceptual, and actual implementation should model these variables with real data. Furthermore, the decision will likely depend upon differences in costs of restoration in these different areas and habitat goals within the watershed or region (e.g., a goal of some improvement versus a certain total level of productivity that may achieve recovery of fish populations).*

Note that determining what is "possible" and "cost effective" is best evaluated within a context of specific goals. If goals are to achieve a certain level of fish productivity in a watershed and potential sites to do this work are limited, then what is determined to be possible is likely greater than in watersheds with many sites to achieve goals. Also, in watersheds with specific fish productivity goals with limited

sites, the willingness to spend more logically could be higher. If goals within a watershed are simply to make fish productivity better than existing conditions and sites to do work are ample, then doing the most cost effective project is the best approach.

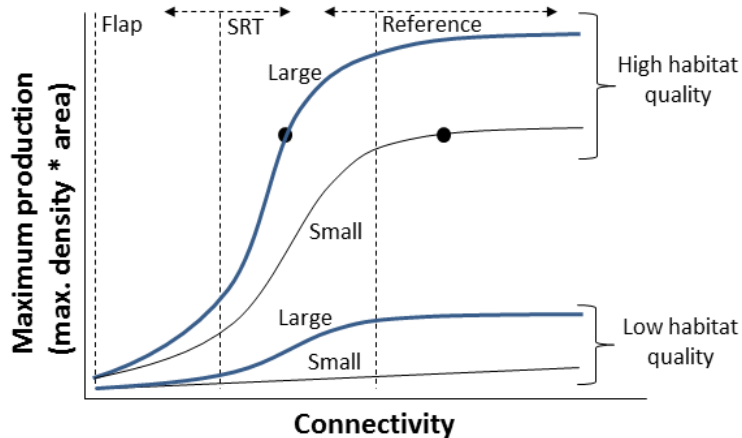


Figure Q15. Hypothetical relationships among maximum production and connectivity for large and small systems with high or low habitat quality. Black dots are at equal levels of maximum production in large and small systems.

Recommended future study: Keep in mind that the study examined SRTs that were currently being used, so the range of variation in juvenile Chinook salmon densities that we observed couldn't consider what might be with better design or operation. Innovation in tide gate design and operation that seeks to maximize connectivity should be encouraged and hopefully these systems will facilitate rearing by salmon.

Q16 The discussion focused on how well SRTs might function as a restoration alternative to dike removal or breaching. SRTs are being installed in growing numbers not as a restoration action, but as a way to improve habitat and fish access for more managed areas where the other alternatives being considered are repairing or replacing existing flap gates. Are there management applications for these types of actions that would be beneficial?

Response: As noted above and in the report, SRTs as currently designed have higher connectivity than flap gates, and may improve upstream use by juvenile Chinook salmon by a statistically small amount (i.e., not easily measurable against the background of variation). Small changes in density could equate to a lot of increased capacity if it were shown that a large area upstream of the gate was restored and used by fish. Independent of benefits for salmon, SRTs might be an economical replacement for maintenance of channels that get choked with invasive freshwater aquatic vegetation.

Recommended future study: This study focused on benefits of tide gates to fish. The question about whether SRTs provide other ecosystem benefits like weed control is worth examining.

Effect on juvenile Chinook

Q17 What are the reasons why juvenile Chinook may be reluctant to swim through SRTs? What other factors are there besides reduced connectivity that may be relevant? Are there ways to test whether

other factors, such as length and cross section configuration of an inlet channel, presence of roughness, shading, or channel complexity may be relevant? Information of this kind would be very helpful for improving the engineering and operational design of SRTs, inlet channels, headwalls, and related infrastructure?

Response: See the response to Q8 above. Everything hypothesized in the above question could influence fish passage, including length of structure, its roughness, etc. – even shading and noise (road crossings at some sides may influence results if they are busy highways or train tracks). Studies of marked fish can address some of these issues. Regardless, understanding how door opening (open/closed and how wide) varies with depth, current direction and velocity (see also Beamer and Henderson 2012) is needed.

Recommended future study: Complete the study/monitoring already recommended – sites with varied design and then monitoring each site with varied operation over several years.

Q18 Among the three SRTs there was a wide range of differences in the percentage of time that the doors were open and that fish could move upstream. How do differences in connectivity relate to different operation management plans versus design differences? How does that then influence how "friendly" a SRT is for fish passage?

Response: It is not known whether design changes vs. changes to operations and maintenance is likely to lead to improvements in how "friendly" an SRT is for fish passage. Estuarine fish can only access habitat upstream of tide gates when its doors are open and water conditions (e.g., depth, current direction and velocity) are physically and behaviorally suitable for fish to move upstream. Tide gate designs can potentially influence some of the variables important to fish by increasing the structure's cross sectional area relative to the channel size, lowering the invert elevation relative to channel thalweg, and varying when (and how wide) doors are open during the tidal cycle. However, we may find door opening results for all tide gate designs correlate similarly with critical upstream fish passage variables (e.g., water depth, current direction and velocity) for all tide gate designs. If this is the case, then beyond making tide gate cross sectional areas larger and setting gate structures lower in channels, fish friendliness will be a function of tide gate operation and is more a matter of how close to conditions of reference channels the tide gate can be operated (i.e., doors always open, no difference up/downstream in depth or water current direction and velocity) at that particular site.

Recommended future study: Complete the comparative study (monitoring) already recommended – monitor fish, environment, and operation at a number of tide gate designs and experimentally vary operation.

Statistical Analysis

Q19 Can you describe more explicitly how reasonable the cumulative density statistic is for describing gate performance? Has this statistic been used elsewhere and is there an indication of how variable this statistic may be from year to year? It involves calculating an average monthly density, which is presumably based on averaging the results from each sampling event at a site in a given month. Relatively intensively monitored sites may be sampled twice per month. Do fish densities have sufficiently low variability that 2x per month is suitable for calculating a monthly average? For long term, intensively and extensively monitored watersheds, this statistic may be appropriate. However a more detailed explanation of its reasonableness for short term monitoring of specific project sites where gate operations or other conditions may vary during the sampling period, is warranted for this report.

Response: The cumulative fish density statistic was used for this study to more simply report results from many sites in an efficient manner. Cumulative Chinook density calculates a result for the season when fish are present in the delta which is what we are concerned about – providing an opportunity for fish to use habitat upstream of tide gates during the overall fish use period. This statistic is robust against within season variability (e.g., zero fish catches on some dates within the season, missing sampling days within the season) by making one estimate for the entire season for a site. However, it can reduce power in an analysis because it is only one result for an entire season at a site.

For example, at Fisher Slough, up/downstream fish catch records were completed without any missing data. ANOVA analysis showed strong differences in up/downstream juvenile Chinook density in 2010 (Beamer et al. 2011) which differed from results in 2009 (before floodgate replacement). Calculating the Chinook ratio result from individual sampling dates during 2010 does not change the overall relative result for Fisher Slough compared to using Chinook ratio result from the cumulative density method (see table below) although the exact numbers between methods are different. Across the season, a sampling event was never observed in which Chinook density upstream of the floodgate surpassed density at the reference site.

Table Q19. Comparison of cumulative Chinook density and biweekly Chinook density metrics for Fisher Slough in 2010

Method	Range that occurred within season	Season Average
Density by individual sampling date		
Reference site	0.21-17.84	4.67
Upstream of floodgate	0.0-2.69	0.71
Cumulative density statistic		
Reference site	NA	2.42
Upstream of floodgate	NA	0.25

Q20 The first paragraph of the discussion notes that SRTs create poorer habitat potential upstream, but the results sections noted weaker site type effects on salinity and temperature. What data were used to support this conclusion?

Response: The study found two conditions in which SRTs had poorer habitat characteristics than reference sites: higher minimum temperatures and lower mean surface elevation (Table 5). In other studies (e.g., Brett 1952, Brett et al. 1982 Beamer et al. 2005, Beechie et al. 2005), juvenile Chinook salmon are sensitive to both habitat parameters. Both parameters are likely related to connectivity. Sites with higher connectivity will tend to allow more flooding and thereby raise mean surface elevation, and added flushing of more connected sites likely results in lower temperatures.

Recommended future study: Several other types of habitat characteristics were not sufficiently investigated in this study, including benthic conditions (and their ability to support prey), riparian cover as influenced by inundation patterns, and prey availability. The samples processed for surface prey availability suggest little difference between SRTs and other systems, but variation was quite high.

Q21 The report states that the percentage of time that gate doors were open increased from 83% to 93%. In the 2009 Fisher Slough Fish Report (page 15) it says that the gates were closed 34% of the time. This implies that the gates were open 66% of the time in 2009. How was the 83% figure calculated? The time that gates were open and water velocities likely too high for juvenile Chinook to swim upstream was 17% (100-17=83) but this isn't the same as % time that gates were open. The estimated juvenile Chinook passage opportunity that reported was 100-34-17=49%.

Response: The original report incorrectly specified some incorrect values pre-restoration, which have been corrected in the report included in this document and in the table below. Differences between the correct values and those reported in Beamer et al. (2010) reflect differences in the time period examined, and the 2009 report examined a subsample of days within the entire juvenile Chinook spring migration period. Note below that the percentage of time a fish could move upstream is a subset of the percentage of time gates were open, reflecting elevated ebb velocities during periods in which gates were open.

Table Q21. Connectivity-related percentages measured at Fisher Slough.

	2009	2010	2011
% of time gates were open	71.7	90.0	93.0
% of time tide not strongly ebbing	73.8	55.0	53.7
% of time fish can move upstream	45.5	45	46.8

Addressing Information Gaps

Q22 What are the most critical remaining knowledge gaps regarding tide gates that could be addressed through targeted project monitoring or broader research in the future – knowledge gaps that would significantly improve restoration practice once filled? How can the limited monitoring budgets usually associated with individual projects be most effectively aligned to address critical questions? The report has one paragraph addressing future study, mentioning SRTs in the context of sea level rise, and the testing of better designs focused on high connectivity and low maintenance. Surely there are other high priority questions that project monitoring can inform? For example, the potential for adaptive management of gate operations to improve function seems to be largely ignored in the restoration community. With some guidance and prodding it seems that this could be an avenue of relatively inexpensive learning.

Response: The study described the ways a number of SRTs currently function. As pointed out in the question, there are likely ways to improve operations. A big information gap is how much improvement can be made by changing design and operations toward optimal levels of connectivity, without compromising the functionality of the site (e.g., maintaining drainage and low soil salinity). How much connectivity can be gained by changing operation? At what point does improving connectivity start impacting site function? How does this level of connectivity compare with optimal levels for fish? Projects that were designed, implemented, and monitored with these information gaps in mind could provide information crucial for adaptive management of SRTs elsewhere.

A second information gap is the relative benefits and costs of other restoration alternatives. This is the best way to put usage of SRTs in context of other alternatives. Some of the above questions are framed from the perspective that certain restoration alternatives are not possible. This may be the case, but in many cases the relevant data are not available. Below are some examples of data that could improve

our understanding about the benefits and costs of various types of estuary restoration, and thereby allow managers to make decisions in the context of the best available science:

- 1) How do juvenile Chinook salmon respond to various types of estuary restoration?*
- 2) How are soil salinity, moisture, and drainage affected by SRT design and operation?*
- 3) How do vegetation communities (riparian environments, wetland plants) respond to design and operation of SRTs and other restoration designs?*

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APPENDIX B

BIOLOGICAL AND PHYSICAL EFFECTS OF 'FISH-FRIENDLY' TIDE GATES

Final Report for the Washington State Recreation and Conservation Office

January 2012

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Summary

A number of restoration techniques exist to counter widespread estuary habitat and connectivity loss across the Pacific Northwest, ranging from dike breaching and removal to installation of “fish-friendly” or self-regulating tide gates (SRTs). However, the physical and biological effects of these techniques have not been rigorously examined. In this report, we focus on the effects of SRTs, and examine their effectiveness in two different ways. First, we used a spatially extensive design to compare three site types: SRTs, flap gates, and unimpeded reference sites. The study compared ten SRT sites located from the Columbia River estuary north to Samish Bay in northern Puget Sound, five traditional flap gate sites (designed to drain freshwater but prevent tidal inundation and saltwater intrusion), and five unimpeded reference sites. Second, we used a temporally extensive design at three SRT sites to determine changes in upstream cumulative densities of Chinook salmon across the rearing season, relative to downstream values, before and after SRTs were installed.

In the spatially extensive study, we studied physical metrics upstream and downstream of tide gates and at reference sites during three visits spanning the primary spring-summer fish rearing period. We also sampled fish and invertebrates above and below tide gates and at reference sites. We found that site type appeared to affect a number of physical metrics including connectedness, water elevation, and temperature, but the degree to which each of these site types affected these physical metrics varied. In addition, densities of Chinook salmon (*Oncorhynchus tshawytscha*) and estuary rearing fish species were much greater at reference sites compared to sites with either flap gates or SRTs. For other species, overall patterns did not strongly distinguish densities between reference sites and flap gate or SRT sites.

In the temporally extensive study, the upstream/downstream ratio of Chinook salmon cumulative density at all SRTs was higher than at a traditional flap gate. The cumulative density ratio at this site increased 6-fold after a passive flap gate was replaced with an SRT, indicating that SRTs can improve habitat use by salmon. However, cumulative density ratios decreased 7-fold when a passive and manually manipulated side-hinged gate was replaced with a SRT, and this measure at all three SRT sites was an eighth to a tenth that of reference channels.

Together, these findings indicate that SRTs vary substantially based on design and operation and consequently vary in performance, depending upon the metric of interest. For estuarine-dependent species in general and juvenile Chinook salmon in particular, SRTs support habitat use above gates much less than natural channels and a little better than traditional flap gates. For other anadromous salmon species that may spawn in creeks above tide gates, SRTs do not appear to strongly inhibit passage or juvenile rearing density. These findings suggest that estuary restoration with SRTs will have limited benefits for juvenile Chinook salmon and other estuarine-dependent species, but can result in some improvement in connectivity and rearing habitat quality compared to traditional flap gate designs. SRT designs and operation standards that maximize connectivity, and site selection criteria that focus on reconnection of large amounts of habitat may overcome some of the limitations of reduced habitat use associated with SRT installation. These potential reductions can successfully be evaluated by comparing the benefits of SRT installation with those of other estuary restoration techniques (e.g., dike breaching or setback).

Introduction

Estuaries in the Pacific Northwest are important nursery areas for a number of ecologically, commercially, and culturally important species, including forage fish (e.g., herring and surf smelt), flatfish (e.g., English sole and starry flounder), and Pacific salmon (e.g., coho, chum, and Chinook salmon). These areas constitute critical habitat to chum and Chinook salmon populations listed under the Endangered Species Act (ESA), which have declined due in part to habitat loss (Hoekstra et al. 2007). Estuarine habitat loss has been implicated in variation of productivity for some fish stocks (e.g., English sole, Rooper et al. 2004; Chinook salmon, Magnuson and Hilborn 2003). Therefore, reducing estuary habitat loss is an important component for restoring ESA Threatened or Endangered populations.

Most of the original estuaries around Puget Sound, the Columbia estuary, and along the Western US coast have been surrounded by dikes that prevent tidal inundation, allowing the land to be used for agriculture, industry, or housing. In Puget Sound, it has been estimated that 80% of estuary habitat has been lost to diking and land conversion, and loss in the Columbia River estuary exceeds 65%. The typical pattern of habitat conversion is the building of dikes to prevent tidal inflow, and installation of culverts to drain rainwater and stream flow from relict sloughs. These culverts are normally fitted with traditional top hinged “flap” gates. Flap gates are designed to limit hydraulic connectivity by passive action, opening during ebbing tides to allow freshwater runoff to drain and closing on the rising tide to prevent tidal flows back into the diked area. Consequently, flap tide gates can prevent passage of adult and juvenile fishes, and change the ecological characteristics of the former estuarine wetlands into freshwater marshes and dry land.

One proposed solution to restore the loss of estuarine wetlands is the substitution of traditional tide gates with other kinds of tide gates that enable inflow of tidal water into the diked areas and (theoretically) improved connectivity for fish (Giannico and Souder 2005). This partial inflow of tidal water would ideally restore some of the wetland structure and function required by salmon and other estuarine-rearing fish, and would allow some degree of fish passage for migration and habitat use. These “fish-friendly” tide gates (also called self-regulating tide gates or SRTs) can vary greatly in design and operation. Gate doors can be a vertical flap or side-hinged, and can even include a “pet door” within the larger door that opens independently of the main door. They can be mounted to a simple headwall, or onto culverts at variable elevation. Operation of SRTs can vary in how long the gate remains open and how wide the opening is, and these automatic operations can often be manually overridden for certain time periods. Given this variation, it is unclear how well SRTs improve access and quality of estuarine habitat, compared to other restoration options (e.g., dike breaching, dike setbacks). Hence, it is unknown how well fish-friendly tide gates actually restore connectivity and rearing habitat to estuarine-dependent species (Giannico and Souder 2005).

In this report, we examine physical and ecological characteristics of ten existing SRTs. In a spatially extensive study, we compare these metrics at SRTs to the same measurements at flap gates and reference sites. In the temporally extensive study, we examine Chinook salmon density across the juvenile rearing season at three SRTs over multiple years during which tide gate design and operations changed. We compare measurements at these “treatment” sites to open-channel reference sites. In both studies, we ask: how do SRTs influence local hydrologic processes and habitat use by aquatic organisms?

Methods

We used two types of designs to examine the physical and ecological characteristics of SRTs: 1) A spatially extensive study taking place within one year, 2) A temporally extensive study occurring over several years. In the spatially extensive study, we examined physical and biological indicators at several estuaries with SRTs in comparison to those with flap gates or ungated reference sites. The benefit of a spatially extensive design is the ability to examine multiple SRTs and reference sites to one another during the same period of time to best understand the range of variation by which SRTs influence physical and biological processes. In the temporally extensive study, we monitored three SRT systems for changes that may have occurred over a period of years starting before, or just after their installation. We focused on three SRTs that have been monitored over multiple years using a post-installation or before-after-control-impact (BACI) design. These case studies provide intensive biological monitoring with some physical monitoring to better examine the success of SRT installations.

In both studies, we hypothesized that connectivity was a primary driver of the physical and biological characteristics we measured. In aquatic systems, this general concept has been used in a variety of contexts, ranging from the hydrologic connection among sites at a local level (Bottom et al. 2005) to systems at more regional scales (Beamer et al. 2005, Schick and Linley 2007,) to the interdependence of life histories of organisms that move among aquatic habitats (Able 2005). This range reflects a temporal dependency corresponding to the residence time of the water column and mobility of the organisms of interest: connectivity at the local level corresponds to movements that could occur within a day, while the larger-scale metrics might be interpreted at weekly, monthly, or annual or even longer time scales. In this report, we examine connectivity in the context of hydrologic connections at a very local level (sites within 0.5 km of each other), and use several metrics that characterize connectivity in the horizontal, vertical, and temporal dimensions (Table 1, see below for details on calculation). Horizontal metrics of connectivity focused on the degree to which two sites are connected in the horizontal plane (e.g., the proportion of the total channel width through which water can pass, or the maximum velocity of water flow, which can directly influence fish movements up and down a channel). Vertical metrics focused on connections that depended upon tidal variation in surface water elevation (e.g., maximum mean high water). Temporally-dependent metrics focused on diurnal changes in connectivity in the other dimensions (e.g., the proportion of time tide gate doors were open).

Spatially extensive study

Study design. This study was designed to determine the degree to which SRTs restored connectivity and its associated effects, compared to reference systems and systems designed to have very low connectivity (culverts with flap gates). We studied SRTs in five different systems across Washington and Oregon: Samish and Padilla Bay, Swinomish Channel, the Skagit River tidal delta, the Chehalis River, and Young's Bay (Fig. 1, Table 2). Within each system, we chose one reference site, one flap gate site, and up to three SRT sites (Table 2, Fig. 2), resulting in a total of 10 SRTs. This design allowed us to examine a wide range of SRTs and to control for local estuary conditions or distributions of particular fish species. SRT sites could vary greatly in culvert dimensions (Table 2), design (side-hinged or flap, with or without a pet door set within the larger side-hinged or flap gate), and number of passive tide gates at the site (Table 2, Fig. 2). We visited each system three times between March and July 2011 to provide replication at the site level, and these visits were timed to observe known temporal windows of rearing by salmon and other estuary-rearing fish. Visits constituted a two-week observation period during which we

monitored sites with dataloggers in both spring and neap tides and sampled abundance of fish and their potential prey during spring tides.

Physical monitoring. We deployed several types of data loggers to monitor hydrologic variation over the three two-week observation periods (Fig. 3). We used Solinst® Levelloggers (3001 LTC F30/M10) to characterize water level, salinity, and water temperature upstream of each tide gate and at each reference site. A combination of Solinst® Levelloggers, Global Water® Level Logger (WL15) with an iButton® Temperature Logger (DS1922T-F5#), or Hobo® Water Level Logger (U20-001-04) sensors were deployed downstream of each tide gated site to measure water level, salinity (only at sites with Solinst® Levelloggers), and water temperature. These sensors were installed one to two days before the first biological monitoring event at each site and no later than the low tide preceding the first biological monitoring event at each site (see below). Each sensor was set to record at one-minute intervals and all sensors were retrieved 10 - 14 days after installation to capture changes in water elevation, salinity, and temperature during all fish monitoring events and both neap and spring tidal cycles.

We deployed sensors in 5 cm diameter slotted PVC monitoring well casings that were secured at each site to prevent sensor fouling and to maintain each sensor at a known elevation (see Elevation Survey methods below). Pressure data obtained from Solinst® Levelloggers and Hobo® Water Level Loggers were compensated using barometric data collected with Solinst® Barologger (LT F5/M15) or Hobo® Water Level Loggers, deployed during each monitoring period to obtain water depths. Global Water® Level Logger data were compensated with the integrated barometric sensors to obtain water depth. Water elevations were calculated from the compensated water depth data series based on known elevations for each monitoring well and the depth of each sensor in each well.

We also installed Hobo® Tilt Loggers (Pendant G UA-004-64) on each tide gate to measure gate movement at one-minute intervals during each 10-14 day monitoring period. For flap gate sites and one top-hinged SRT, tilt loggers were deployed in watertight PVC canisters that were secured to the tide gate itself (Fig. 2J). On side-hinged SRTs, tilt loggers were installed on a chain that translated the horizontal movement of the gate's control arm to a vertical change in chain tension.

We also measured water velocity at each site between June and July 2011 using HACH® Ultrasonic Submerged Area Velocity Meters (Sigma 950) that were deployed for approximately 24-hours at each site. The flow sensors were secured to a telescoping pole that could be positioned in the vault or culvert at each gated site or to the monitoring well at each reference site. The telescopic pole was positioned so that the sensor was 7 cm above the ground in the middle of the culvert, vault, or channel floor. The flow sensor measured water velocity and level at 1-minute intervals during each 24-hour deployment. The flow sensor was positioned so that positive velocities indicated net flow into the channel and negative velocities indicated net flow out of the channel.

Biological monitoring. We collected biological samples three times at each of the 10 SRTs, 5 flap gate, and 5 reference sites, for a total of 60 sampling events. Biological samples consisted of 1) fish, amphibians, and large invertebrates captured in beach seines or fyke nets, and 2) samples of small invertebrates collected using a neuston net.

With the exception of two reference sites, we sampled fish and other large aquatic organisms using 3 mm mesh beach seines that were 25-31 m long by 2-3 m deep with a tightly

corked float line and continuous lead line. We sampled each site during high water, focusing on a pre-determined sampling area and depth distribution that could be completely sampled by any of the nets we used. At tide gate sites, we sampled one site below and above the tide gate adjacent to the end of the culvert, but geomorphology, vegetation, and large debris required us to locate some sampling sites as much as 200 m away from the culvert. At the five reference sites, we chose two replicate sites to sample within 200 m of each other. During beach seines, we circled the predetermined sampling area with the net and hauled the net up onto a beach at which the net could be properly stacked. All fish captured in the net were counted and up to 25 of each species were measured for length. Absolute counts were converted to densities by dividing by sampling area.

Due to natural constraints, two of the five reference sites used in the temporally extensive study were sampled using fyke nets instead of beach seines. In these cases, a fyke net with a funnel trap was deployed across the channel at high tide, and fished while the tide ebbed (see below). At low tide, all captured fish were collected from the cod end of the net and counted and measured just like beach-seined samples. Fyke trap abundances were converted in a straightforward fashion to density by expanding catch by recovery efficiency and dividing by the high-tide channel area above the trap (see below).

During each of the three visits, we also collected invertebrate samples from both above and below the 15 tide gates (180 samples total) and at one of the beach seine locations for the five reference sites (30 samples total) using two replicate tows of a 110 μ m neuston net towed 30 m. After each tow, the net was rinsed from the outside to remove invertebrates from the net, and the sample was sieved from the cod end of the net into a bottle with 10% buffered formalin for post-survey sorting, identification, and counting. In the lab, we focused on the larger taxa by sieving water samples through a 500 μ m sieve, and we categorized taxa into marine/estuarine or freshwater groups. Due to the complexities of invertebrate taxon identification, we were subsequently able to identify taxa in only one of the two replicates from the second visit, although we did compare replicates of five samples to evaluate sampling variation (40 samples total processed).

Elevation surveys. We completed high resolution Real Time Kinematic (RTK) GPS surveys to determine elevation and position data on key features at each site. At SRTs and flap gate sites, upstream and downstream monitoring wells as well as upstream and downstream invert (culvert lip) were measured using three-second occupations with a rover and onsite base station (Trimble® R8). RTK surveys at reference sites were limited to the single monitoring well at each of these sites. At SRT sites, we also collected upstream channel thalweg measurements at accessible locations upstream of the tide gate to determine the upstream extent of tidal influence within the channel. Because of private property issues, we did not survey upstream of flap gates and reference sites, so these measurements at SRTs are reported without analysis (Table 2).

All RTK survey data were differentially corrected using two-hour Post Processed Kinematic (PPK) surveys of base stations that were established at each site. Position solutions for these two-hour PPK surveys were obtained from the Nation Oceanic and Atmospheric Administration's (NOAA) Online Positioning User Service (OPUS). All GPS data were collected using the NAD83 UTM Zone 10N coordinate system and processed using the NAVD88 (GEOID09) vertical datum from the static two-hour PPK base station observations.

Physical data processing. Tilt data were used to classify the position of each gate as open or closed during each one-minute interval. The position of the gate was then used to summarize the proportion of time each gate was open and the average, maximum, and minimum water elevation, temperature, and salinity during open and closed periods for each monitoring period above and below each tide gate. Reference sites were considered open at all times for all data summaries. Water levels occasionally dropped below the elevation of the data logger during some tidal cycles at certain sites. In these cases, data from these sensors were not used to calculate water elevation, temperature, and salinity summaries.

The maximum water elevation observed upstream of each self-regulating tide gate was compared with upstream thalweg elevation measurements to determine the channel length of tidal influence upstream at each site. We estimated tidally-influenced channel lengths based on distance measurements along the middle flow path of the primary channel, from the tide gate to the upstream-most point where thalweg elevations were less than the maximum upstream water elevation.

We also used tilt data in combination with water level to calculate connectedness, i.e., the proportion of time a given tide gate was open and when the downstream culvert invert was perched no more than 10 cm above the downstream pool surface, indicating time periods in which juvenile fish could physically enter the culvert and when water was not cascading through the channel and creating an impassible waterfall at the culvert base. At reference sites, connectedness equated with whether the site remained covered with water. Hence when water level was ≤ 0 , connectedness for reference sites was also 0.

While tide gates in theory should eliminate connectedness when closed, we observed that certain tide gates could be “leaky,” allowing some water flow after the gates had closed. Leakiness was detected using the velocity probes. As shown in Fig. 4A, nonleaky tide gates were characterized by a high in-flow pulse right at gate closing, followed by near-zero velocity until gates opened up, after which high outflow was observed. However, in some cases (Fig. 4B), velocity spikes could be detected after gates had closed, indicating movement of water despite gate closure. We calculated a leakiness index by dividing the cumulative velocity flux (i.e., velocity in or out, summed across recording intervals) during gate closure by the cumulative velocity flux across the entire monitored time period. For reference sites, which lacked a “closed” period, the tide is either flooding or ebbing without flux in the opposite direction. Hence leakiness for reference sites is 0.

Biological data processing. We adjusted abundance data by sampling area to calculate density of each species. We then focused on several indicator taxa (Table 3): Chinook salmon (the most ecologically sensitive estuarine-rearing species), three-spine stickleback (the most common species), total density of anadromous fish (any fish that spawns in freshwater and migrates from freshwater to the ocean during juvenile life stages), total density of estuarine-dependent species (species with key life stages in estuarine habitats), total density of nonnative species, and % of neuston invertebrates that were estuarine (i.e., do not inhabit freshwater).

We expected biological data to be highly variable and system-dependent. To reduce variation and simultaneously account for system-specific density or distribution, we transformed data using the formula:

$$I = \log_{10}[(0.001 + d_{t,s})/(0.001 + d_{r,s})]$$

where I is the relative density, d_s is the density of indicator d at site t in system s , and $x_{r,s}$ is the density of indicator x at the upstream reference site of system s . Hence, this equation indicates the orders of magnitude above (positive values) or below (negative values) which a given site differs from the upstream reference site. The addition of 0.001 in the numerator and denominator allows for situations in which a given indicator was not observed at the reference site. The equation indicates that the reference value is expected to be 0, although variation from 0 can occur because of replicate sampling at reference sites. For the % estuarine neuston index, reference site values always equal 0 because they were sampled at only one reference area.

Statistical analyses. To examine the effects of site type (flap, SRT, or reference) on physical and biological metrics measured at multiple visits, we used general linear statistical models (GLM) that focused on site as the sample unit. Site type, geographical system, sample location (upstream or downstream), and their two-way interactions were modeled as fixed effects, while visit and its interactions were modeled as repeated measures. We first performed multivariate GLMs to take advantage of covariation across multiple possible physical or biological metrics. Analysis of physical metrics included connectedness, water level relative to downstream invert (min. and max.) during periods when tide gates were open, and water surface elevation (min., mean, and max.), salinity (min., mean, and max.), and temperature (min., mean, and max.) during periods when tide gates were closed. Leakiness and velocity were not included because they were measured only once during the study. Analysis of biological metrics included all indicator groups (Chinook, stickleback, estuarine-dependent, anadromous, and nonnative), but not neuston scores because they were analyzed for only one visit. Multivariate GLMs included all data points and explicitly modeled upstream and downstream location comparisons. Thereafter, we used univariate GLMs focused on just upstream sampling locations to examine how specific metrics were influenced by site type. For metrics that were measured just once during the study, we used standard Analysis of Variance (ANOVA). We performed post-hoc comparisons of site type using Fisher's least significant difference (LSD), and set level of significance at $p < 0.05$.

Temporally extensive study

Study design. The goal of this study was to determine how well SRTs function over time as rearing habitat for juvenile Chinook salmon, relative to conditions at reference sites that were not modified during the course of this study, and (at two sites) to conditions measured before SRTs were installed. Hence, this study examined temporal aspects of tide gate function over multiple years. We focused on three SRT installations that were also included in the spatially extensive study: McElroy Slough, Fisher Slough, and Fornsby Slough (Fig. 5). The first two sites are characterized by a watershed upstream of tide gates that is large enough to support spawning by coho and chum salmon, but none of the three watersheds support spawning populations of Chinook salmon. All three sites provide estuarine habitat that can support juvenile rearing by these three salmon species as well as other estuarine-dependent species.

All sites underwent extensive restoration. At McElroy Slough, three flap gates were replaced with a side-hinged SRT and three passively opening flap gates in 2006 (Table 2, Fig. 2A). Very little habitat improvement occurred at McElroy although culvert replacement upstream of the SRT site also improved tidal connectivity. Restoration at South Fornsby Slough involved a number of phases, including replacement of a flap gate with a side hinged SRT, channel modification to allow for a marsh surface adjacent to the channel, and revegetation. Tide gate replacement at South Fornsby occurred in late summer 2005 (Table 2, Fig. 2D). Operation

of both the flap gate and SRT varied over the course of the BACI study, with manual or entirely passive operation existing during our monitoring period for years 2004, 2005, and 2007. At Fisher Slough a three door, side hinged SRT system with two small submerged flap gates (one passive; one with manual capability) was installed in August 2009. This structure replaced an old set of paired wooden, side-hinged doors, hung on three separate openings with two additional submerged openings with passive flap gates. Dimension of openings and elevations remained the same (Table 2, Fig. 2E). Extensive habitat restoration (e.g., dike setback, channel relocation, revegetation) upstream of the SRT site occurred in the summer of 2010 and 2011, and SRT gates remained closed to prevent tidal inundation through this time period. However, treatment effects of habitat change (quantity or quality) did not influence this study's examination of SRT installation, because habitat restoration was designed not to affect hydrological processes until 2012. Hence, the monitoring captured changes in gate design and operation but not ongoing habitat restoration.

Restoration effectiveness of the three tide gate sites was studied using different restoration monitoring designs. Fornsby and Fisher Slough were monitored using a BACI design starting one (Fisher) or two (Fornsby) years before SRT installation and for at least two years post-SRT installation. McElroy Slough was a post-treatment design with four years of monitoring over the six years the SRT has been in operation. Tide gate operation varied by site and year. At Fisher Slough, the pre-SRT structure operated as a traditional passive side-hinged flap system most of the year with the doors held manually open during late spring through the summer. After SRT installation, the gates were set to close when tidal or Skagit River backwater flooding exceeded a set elevation which varied by management periods described in the site's Hydraulic Project Approval (HPA) (2.29 m NAVD 88 during fall and winter flood management; 2.90 m NAVD 88 during juvenile Chinook salmon migration; gates are to remain open during the summer irrigation period). The McElroy Slough SRT was set to close when tidal flooding exceeded 1.68 m NAVD 88. Reference sites for Fornsby and Fisher Sloughs were determined pre-treatment, and all three sites were compared to long-term monitoring reference sites in the region. All sites were monitored both above and below the tide gate using data loggers and a combination of beach seine and fyke trapping methods (Table 4). The sampling period was selected to coincide with the Skagit's juvenile Chinook tidal delta residence period (Beamer et al. 2005, i.e., from February to August), although this sampling period varied slightly among sites but not between strata within sites (reference, upstream, and downstream).

Monitoring locations at each tide gate were selected systematically downstream and upstream of the tide gate to represent the habitat types and spatial diversity within the project area (Table 4). Sampling sites were selected in order to compare juvenile Chinook salmon densities above the tide gate to that below the tide gate. In addition to examining reference sites associated with the Fornsby and Fisher BACI designs, we compared tide gate data with additional long-term status monitoring reference sites at a variety of locations in the Skagit River estuary. For these sites, "upstream" monitoring was the reference site itself, while "downstream" monitoring occurred in tributary channels connecting these sites to Skagit Bay. These additional sites provided better ranges for both environmental data and fish densities over time than just the two BACI reference sites could.

Environmental monitoring. We measured selected environmental variables at each site at the time of beach seining or fyke trapping to assess their potential influence on biological data across sites in the study area. We used Solinst® Levelloggers (3001 LTC F30/M10) to characterize

water level, salinity, and water temperature upstream and downstream of each tide gate and at each reference site, which were set to record continuously at 15-minute intervals throughout the sampling period. Pressure data obtained from Solinst® Levelloggers were compensated using barometric data collected with Solinst® Barologger (LT F5/M15) deployed in the vicinity of each site. Data loggers were placed in standpipes upstream and downstream of the tide gate, whose elevation was determined via RTK surveys (see elevation surveys, above).

In addition to data logger recordings, water temperature and salinity (ppt) were measured by the fish sampling crew at the time of the beach seine or fyke trap sample at each site using a YSI® Professional Plus Model meter. Multiple readings were taken at the surface and at the bottom of the water column within the beach seine or fyke trap set area. The values were averaged by surface or bottom for each sampling day and site. In addition, velocity was measured at each beach seine site using a Swoffer® Model 2100 flow meter. Four measurements were taken across the area seined after the set was made, and the average value of these readings was reported for each site/date combination.

Biological monitoring. We used two types of nets to sample fish at tide gate and reference sites. Most sites were sampled using a 24.4 x 1.8 m beach seine made of 3 mm knotless nylon mesh. The net was set in a “round haul” fashion by fixing one end of the net on the beach while the other end was deployed by walking or boat-towing the net “upstream” against the water current (if present), and then closing the net by returning to the shoreline in a half circle. For each beach seine set, we recorded the time and date of each set, the percent of set area (the area that the net covers compared to setting in a perfect half circle), and the maximum depth (m) of each beach seine set, taken by the fish sampling crew at the time of the sample at each beach seine site using a calibrated measuring rod. These measurements allowed catches to be converted into density estimates (see below, also Beamer et al. 2011).

For small blind channel reference sites that extensively dewater at low tide, we used a fyke trap to sample fish. The fyke trap was constructed of 3 mm knotless nylon mesh with a 2-0.6 x 2.7 m cone sewn into the opening to collect fish draining out of the blind channel site. This trap was set on posts at high tide and fished through the ebb tide, yielding a catch. Channel area measurements, water depth changes, and multiple recovery efficiency tests using groups of marked fish allowed catches to be converted into densities (see below, also Beamer et al. 2011). The maximum depth at the fyke trap site was taken at each set from the surface water relative elevation staff gage located upstream of the fyke trap at the time the trap was installed.

For all fish sampling, we identified and counted the catch by species, and measured individual fish lengths by species. We measured all fish caught by species when the catch for a specific species was 20 individuals or less. For catches larger than 20 individuals, we randomly selected 20 individuals for length samples.

Environmental data processing. For the temporally extensive survey, we focused on variation in measures of connectivity and surface water elevation. Metrics of connectivity included 1) the percentage of time the tide gate was opened, the 2) percentage of time that fish could move upstream, and 3) the proportion of bankfull channel that was open. The first metric was estimated either by angle logger data (described above) or by examining instantaneous changes in water level upstream compared to downstream. The second metric started with the first, but focused only on time periods in which tide was not ebbing (i.e., door is open and tide not ebbing). The third metric was based on simple measurements of open channel width. For

reference sites, this value is 1 because sites are not restricted by fill, culverts, gates or other structures. For tide gate sites, the metric is the combined opening width of structures divided by channel width.

Surface water elevation metrics included % tidal muting and effective water surface elevation at mean higher high water (MHHW). To calculate the first metric, we compared water surface elevation upstream and downstream at MHHW using the NAVD88 vertical datum as a benchmark for sea level. At sites with tide gates, our calculation for percentage of tidal muting (M) was

$$M = 100 \cdot (H_d - H_u) / (H_d - E_i)$$

where H_i is the surface water height at MHHW measured either upstream (u) or downstream (d) of the tide gate, and E_i is the elevation of hydraulic control for the reference channel (r) or tide gate (t). At all reference sites, $M = 0$. To capture the variable nature of surface water elevation across reference sites, and directly compare this to surface water heights above the tide gates, we also examined the effective elevation at MHHW, which is simply H_u .

Biological data processing. For beach seined juvenile Chinook salmon, each set's catch was divided by set area to calculate a Chinook density for each beach seine set. For the fyke trap site, juvenile Chinook salmon catch numbers were adjusted by trap recovery efficiency (RE) estimates derived from three mark-recapture experiments using a known number of marked fish released upstream of the trap at high tide. Recovery efficiency estimates are unique to each site and are related to hydraulic characteristics of the site during trapping. We used the RE results to convert the "raw" juvenile Chinook salmon catch to an estimated population size within the channel network upstream of the fyke trap on any sampling day. The RE-adjusted Chinook salmon catch was divided by the bankfull channel area of the blind channel network upstream of the trap to calculate a juvenile Chinook salmon density. The limits of the blind channel network upstream of the trap were determined in the field. To calculate bankfull channel area, we digitized a channel polygon using high resolution orthophotos and used GIS to calculate area.

For each year of sampling, we estimated the season-long density of juvenile Chinook salmon at all monitoring sites and other long term monitoring sites located throughout the Skagit tidal delta. We term this fish density statistic *cumulative density*. Cumulative density (fish*days*ha⁻¹) expands individual sampling efforts over the entire season using the formula

$$C = \sum_{m=F}^L D_m n_m$$

where C is cumulative density, m is month, D_m is the average monthly density, and n_m is the number of days in the month. The terms F and L are the first and last months sampled, respectively. Normally F = February and L = August, but these months could differ slightly depending upon the site and year (Table 4). Almost all years captured the entire pulse of estuary rearing by Chinook salmon.

We calculated separate cumulative density for upstream and downstream locations, and then divided upstream cumulative density by that downstream to obtain a cumulative density ratio that could be compared across sites, and removed any minor bias associated with variation in sampling period.

Statistical analysis. We examined Pearson correlations among the physical metrics describing variation in connectivity and water surface elevation, and determined whether these in turn correlated with the $\log_{10}$ -transformed ratio (inside/outside) of cumulative density. Level of significance was $p < 0.05$

Results

Spatially extensive study

Physical effects. General patterns in physical metrics over time suggested strong differences between flap, SRT, and reference systems. The most obvious effects were the proportion of time each site type was subject to tidal flux and the resultant water levels during open and closed periods (Fig. 6). The proportion of time open was reduced approximately by half at many SRT sites relative to reference sites, and was reduced even more at flap gate sites, which opened on and ebbing tide when water had accumulated upstream of the gate (Fig. 6). These changes resulted in clear muting of tidal elevation upstream of tide gates. Temperature and salinity also exhibited apparent differences across different site types, but these metrics were more temporally variant, and systematically varied with system. At one extreme, Fisher Slough is essentially a freshwater tributary of the Skagit River subject to variation in tidal height, but little variation in salinity, and at the other extreme is Fornsby Slough, which is heavily influenced by tidal flux and consequently quite saline. Not surprisingly, the multivariate GLM revealed very strong effects of site type, upstream or downstream location, geographic system, and visit, as well as site type*location and visit*system interactions as based on Hotelling's trace statistic ($p < 0.003$ for all).

Univariate analyses of physical effects focusing on upstream data revealed that physical metrics exhibited differential sensitivity to the main effects modeled (Table 5). Of the four types of metrics that focused on connectivity (connectedness, leakiness, and water elevation relative to invert and water velocity during open periods), only connectedness and leakiness exhibited systematic effects of site type or of other main effects and interactions. Connectedness increasingly differed across flap, SRT, and reference sites (Fig. 7A) as determined by post-hoc comparisons (Table 5), with SRTs exhibiting over twice the connectedness of flap gates but nearly half that of reference sites (Fig. 7A). Leakiness showed a strong opposite pattern (Fig. 7C, Table 5), with flap gates having the highest leakiness values and reference sites having the lowest, although no difference was detected between reference sites and SRTs after accounting for other effects. Both connectedness and leakiness exhibited moderate system effects as well as a site type*system interaction, indicating strong geographic variation. Although both water level relative to invert and maximum velocity into and out of channels appeared to show strong patterns across site type (Fig. 7B), these values generally exhibited little statistical difference from each other after accounting for system differences. The exception was a significant difference between flap gates and SRTs in minimum water level relative to invert when gates were open, which also varied systematically across visits.

Of the three remaining physical variables, only water surface elevation during closed periods exhibited systematic variation across site types at upstream sites (Table 5, Fig. 8A). Strong site type differences were observed in minimum, average, and maximum elevation values; post-hoc tests indicated that flap gates had 2-6 times lower water elevation than reference sites and a third to 5 times that of SRTs. In addition, SRTs had a 50% lower average water

surface elevation than reference sites. Water surface elevation metrics also exhibited influences of system and visit, but no strong interactions.

In contrast, salinity and temperature exhibited weaker effects of site type relative to other main effects. Minimum and mean temperature at upstream sites during closed periods moderately differed among site types. Post-hoc tests indicated that flap gates and SRTs tended to have similar values, while reference sites were lower (Table 5, Fig. 8C). This was particularly true of minimum temperature. Salinity and temperature exhibited much stronger spatial or temporal effects, and also exhibited a number of strong interactions among main effects (Table 5).

Biological effects. The multivariate GLM revealed very strong effects of site type, upstream or downstream location, system, and visit, as well as a visit*system interaction as based on Hotelling's trace statistic ($p \leq 0.01$ for all). However, univariate analyses focused on upstream samples of biological indicators indicated that the metrics exhibited great variation with respect to the main effects modeled (Table 5). We focused on two contrasting single species indicators: Chinook salmon and three-spine stickleback. Chinook salmon are listed as Threatened under the Endangered Species Act and rely upon estuarine habitats for juvenile rearing (Healey 1980), while stickleback rear in a variety of freshwater and marine habitats and are tolerant of stressful aquatic conditions (Seilheimer and Chow-Fraser 2006). Both species were commonly encountered at sites during the course of this study (Table 3). However, each species responded differently to the study comparisons and to the range of hydrologic conditions recorded at sites. Chinook salmon densities exhibited a strong overall influence of site type, and post-hoc tests revealed that average densities were over four times greater at reference sites than at SRT or flap gate sites, which had statistically similar densities (Fig. 9A). Chinook salmon densities also exhibited strong system differences and moderate temporal differences, and a very strong system-temporal interaction. In contrast, stickleback densities did not significantly vary across site types (Fig. 9B), and were much more sensitive to visit timing. Stickleback densities exhibited great variation, and average densities were over three times higher at flap gates than at reference sites, with densities at SRT sites appearing more similar to flap gate sites.

Of the four species groups, only estuarine-dependent species exhibited strong effects of site type (Table 5, Fig. 10A). For this group, densities were over an order of magnitude greater at reference sites than at SRT and flap gate sites, which had much more similar densities. Densities for all other species groups were variable enough that they did not exhibit significant effects of site type. However, for percentage of estuarine/marine neuston (Fig. 10B), SRTs most resembled flap gates, and had a higher percentage upstream of tide gates than reference sites. For anadromous and nonnative species groups (Figs 10C-D), SRTs were more similar to reference sites, and both differed from flap gates by 3-6 times, although the very large variability in density across flap gate sites eliminated any strong significant pair-wise differences. Most species groups exhibited moderate spatial variation, and did not show strong interactions between main effects.

The combination of site type, geographic, and temporal elements to the study appeared to robustly explain connections between physical variation and biological metrics. As a simple comparison, we examined raw correlations of physical metrics with the biological metrics, and correlations of the residuals of the physical metrics (i.e., variation not explained by the statistical design) with the biological data (Table 6). Just focusing on the upstream sites, we observed a total of 15 raw correlations of physical metrics with our different biological metrics. At a significance level of 5% 4-5 of these would be expected to occur by chance, suggesting that

some correlations were real patterns. After accounting for our analysis' main effects, only one correlation remained.

Temporally extensive study

Physical effects. Variation observed over time at three SRT sites, including two that were monitored before and after installation, corroborate the spatially extensive study. We focused on metrics primarily related to connectivity and water surface elevation, and how they affected cumulative densities of juvenile Chinook salmon. Both Fisher and S. Fornsby sites exhibited improvements in physical metrics in response to SRT installation. At Fisher Slough, two measures of connectivity exhibited slightly different patterns. The percentage of time that gate doors were open increased from 83% to 93%. However, the percentage of time fish could move upstream decreased slightly from 49% to 47%. The different trends at Fisher are explained by differences in gate operations between pre- and post-SRT years. In 2009 (prior to SRT), the Fisher Slough gates operated as a passive system 60% of our fish monitoring period. For the remainder (40%) of the monitoring period in 2009, the gates were manually held open. After SRT installation, the gates at Fisher were operated to close when water surface elevation caused by tidal or backwater flooding from the Skagit River was greater than a specified elevation per specific management periods described in the site's HPA (see methods above). A major difference in operation between pre- and post-SRT monitoring years at Fisher is that gates were not manually held open for the summer irrigation period in 2010 and 2011 to accommodate habitat restoration and construction occurring upstream of the Fisher SRT. At S. Fornsby, replacement of a flap gate with an SRT increased both connectivity measures by about the same amount: the percentage of time that gate doors were open increased from 28% to 40%, while the percentage of time fish could move upstream changed from 0% to 14%. Post-restoration connectivity at McElroy Slough was 67% and 39% for percentage of time doors were open and time that fish could move upstream, respectively. These connectivity parameters were only measured in 2011 at McElroy. The McElroy SRT was operated the same in each monitoring year so we assume connectivity results from 2011 reasonably represent other SRT years at McElroy.

Surface elevation metrics also exhibited improvements resulting from SRT installation. At Fisher Slough, tidal muting was reduced by roughly half (44% and 26% before and after SRT installation, respectively not including the 2009 period when the gates were manually held open), resulting in 13% increase in effective surface elevation at MHHW. At S. Fornsby, tidal muting declined from 66% to 47%, resulting in a nearly 40% increase in the effective MHHW. Across all sites, physical metrics were tightly correlated with each other (Table 7). Post SRT installation tidal muting at McElroy was 33%.

Biological effects. Increased tidal connectivity appeared to improve cumulative density of juvenile Chinook salmon rearing above tide gates at one of two BACI sites. At Fisher Slough, the replacement of manually and passively operating side-hinged gates with side hinged SRT gates was followed by a reduction in the cumulative density ratio by over 80% (Fig. 11A). This loss in cumulative density resulted in the tide gate cumulative density ratio decreasing from nearly 50% to 10% of Fisher's reference site before and after SRT installation, respectively. The story was different at S. Fornsby Slough, which exhibited systematic variation in the cumulative density ratio in relation to mode of tide gate type and operation (Fig. 11B). The greatest change was a nearly 6-fold increase in cumulative density when a passive flap gate operation was replaced with an operational side-hinged SRT. However, cumulative density ratios under all

types of tide gates and operations were at least 8 times lower than cumulative density ratios at Fornsby's reference site. Although such comparisons are not possible at McElroy Slough (Fig. 11C), cumulative density ratios after SRT installation averaged 0.19 across four years of monitoring, mirroring SRT cumulative density ratios at Fisher Slough. Cumulative Chinook salmon density ratios at all SRT sites were well over an order of magnitude lower than index reference sites across the Skagit River estuary (Fig. 11D).

Across all sites and their modes of operation, cumulative density ratios exhibited strong correlations with all connectivity and surface water elevation metrics (Table 7), so it was difficult to identify a single measure that defined biological performance across all sites. Nevertheless, all variables show a strong ordering of cumulative juvenile Chinook salmon density ratio with 1) passive flap gate operations, which had the lowest levels of connectivity or surface elevation and cumulative density, 2) SRT operations, which exhibited moderate improvement in connectivity and surface water elevation but not necessarily improvement in cumulative density, and 3) reference sites with the highest levels of connectivity, surface elevation, and cumulative density (Fig. 12). Also evident is that passive flap or side hinged gates that are manually over-ridden (i.e., gates held open) during our fish monitoring period were consistently higher in cumulative Chinook salmon density ratio than purely passively operated gates.

Discussion

Our spatially extensive study revealed that by at least one measure (connectedness), SRTs generally reduced connectivity by over 50% relative to reference sites, and that this change appeared to have cascading effects on water surface elevation, temperature upstream of the SRT, and assemblages of estuarine fish. Flap gates reduced connectedness by another 50% relative to SRTs, or 75% relative to reference sites. Reductions in connectivity and water surface elevation should come as no surprise – that is what flap gates and SRTs are designed to do – but it is important to quantify the differences among such sites and how they affect organisms because this provides a sense of how much SRTs represent a “middle ground” in providing both benefits to adjacent land use and estuarine rearing species. Both physical and biological data indicate that whether SRTs are considered more similar to flap gates or reference sites strongly depends upon which metrics are measured. Nevertheless, the physical conditions resulting from SRT placement appear to create relatively poorly connected or unsuitable habitat for estuarine-dependent aquatic species, particularly ESA threatened Chinook salmon. For these biota, the combination of connectivity reductions and changes to habitat potential upstream of SRTs results in low enough densities that those sites more resemble flap gates than reference sites. Whereas, connectivity or physical metrics appear to vary linearly among different site types (e.g., y-axis in Fig. 7A) or tide gate operation (x-axis in Fig. 12), variation in densities of estuarine-dependent species appears exponential by site type.

These findings were further supported in the temporally intensive study and corroborated over multiple years. Our two BACI designs provided the best examples how contrasting structure designs and/or operation may influence biotic results. At S. Fornsby, top hinged flap gate replacement with a side hinged SRT was followed by a 6-fold increase in cumulative Chinook salmon densities, but these densities were still 8 times lower than its hydraulically unimpeded reference site (Fig. 11B). In contrast, the replacement of a passively and manually (depending on season) operated side hinged floodgate at Fisher Slough with a heavily engineered set of side-

hinged SRTs was followed by roughly a 10-fold decline in cumulative density of Chinook salmon (Fig. 11A).

While surprising, the biotic results at Fisher Slough may best illustrate the importance of varying tide gate operations. In 2009 (before SRT installation), the passive side-hinged gates were manually held open starting in June. However, after SRT installation in 2010 and 2011, gates were closed during summer months because of habitat restoration and other construction occurring upstream. Now that the restoration has been completed, future gate operation will include the same “gates manually held open” period starting in June that occurred in 2009, and future monitoring at Fisher Slough will better determine the long term influence of SRT installation and habitat restoration at this site. Given its level of connectivity, we would expect it to perform somewhat better than other SRTs upon normal operation (Fig. 12). In any case, the temporal variation in cumulative densities at SRT sites illustrate that changes in tide gate operations can be just as important as differences in gate design.

The Fisher Slough example also under-scores the importance of monitoring. By having only one year of monitoring data before SRT installation, we have lost the opportunity to know whether 2009 was representative of all pre-SRT installation years at Fisher Slough. We strongly recommend BACI monitoring designs with multiple years for each time period. We also note slight differences in the monitoring period from 2009-2011 (Table 4), but in each year we sampled through the majority of the juvenile Chinook outmigration period, and any variation in density during the unsampled period of time is expected to be a fraction of the cumulative density estimate that was measured. Overall, our conclusion from monitoring this site in the context of other results is that various tide gate designs and their operation that reduce connectivity and mute tidal elevation appear to result in a fraction of the seasonal rearing Chinook salmon density upstream of tide gates, compared to unimpeded reference sites (Fig. 12).

The importance of connectivity. A number of studies have highlighted the importance of connectivity for habitat processes (e.g., Cloern 2007) and fish rearing (West and Zedler 2000) and migration (e.g., Gillanders et al. 2003) in aquatic systems, and we found similar patterns in this study. In theory, the primary benefit of SRTs is increased connectivity relative to traditional flap-style tide gates. Connectivity at SRTs should ameliorate flow conditions on both sides of the gate, thereby allowing muted saltwater inflow on floodtides to support estuarine-sensitive species while removing freshwater from inside dikes on ebb tides. We used several metrics to examine connectivity across horizontal, vertical and temporal dimensions (Table 1), and our analysis suggested that relatively simple metrics could robustly predict the likelihood that a channel’s environmental conditions were modified by the tide gate. In the spatially extensive study, connectedness was just as powerful as site type at explaining Chinook salmon and estuarine-dependent species densities. In our temporally extensive study, a metric as simple as the percentage of the channel remaining open to water passage exhibited a surprisingly strong correlation with cumulative density.

Leakiness, while showing significant differences among site types, is not an ideal indicator since it is not a design feature of tide gates, and mostly serves to indicate that some variation in physical or biological data may be a product of design mis-function. Several flap gates appeared fairly leaky as judged from sounds of rushing water heard during at high tides (when tide gates should be fully closed), and the leakiness values confirm that. But a very leaky tide gate might not equate with high connectivity if it systematically was cracked open enough to

only allow water movement at high velocity. Indeed, we did not find strong correlations of biological metrics with leakiness across the range of leakiness measured.

Other connectivity metrics did not exhibit strong variation across site types, or did not predict fish densities. Depth and velocity should in part determine upstream juvenile salmon habitat use because of physiological or behavioral limits of fish movement. In our study, water level above invert describes how well culverts are submerged during open periods when fish could have access to upstream areas. Peak velocity metrics describe the highest values of velocity in and out of the channel or culvert. Both SRTs and reference sites exhibited peak velocities that surpass exhaustion-inducing swimming velocities in juvenile salmon fry (0.27-0.43 m/s, Flagg and Smith 1979, Giannico and Souder 2005), and at SRTs, these velocities occurred during the shortened time windows in which the SRT is open to passage (Fig. 4). Ecological theory predicts that juvenile salmon would work against strong current mainly when that bioenergetic effort is worth the cost (e.g., higher growth, predator avoidance), and not simply for habitat utilization. On the other hand, extremes in both depth and velocity are not necessarily representative of the entire tidal cycle (Fig. 4, 6), and may not be predictive of fish densities because fish are likely sensitive to these cues and can adjust their behavior to move upstream under preferred conditions. This contrasts with connectedness measures, which explicitly measure the proportion of time in which fish are able to move upstream through culverts. It is likely that that velocity may have been an important constraint on upstream movements of estuarine-dependent species like juvenile Chinook salmon, but the temporal dynamics of velocity changes across the season were insufficiently measured by the study design

Roles of other environmental variables. Clearly, factors other than connectivity play a role in determining whether channels are suitable for fish and other species of interest. For example, in estuarine systems, some species inhabit specific ranges of salinity, and juvenile salmon are notably sensitive to variation in water temperature. We found that water surface elevation and temperature but not salinity were strongly influenced by site type, clearly indicating that tide gates have the potential to modify the local environment in addition to affecting accessibility. By limiting tidal elevation, tide gates also could influence the tidal prism upstream, and as a consequence could affect channel forming processes in habitat both upstream and downstream of flap gate or SRT structures (Hood 2004, 2007).

If accessibility is not constrained by tide gates, fish selecting areas to rear might cue in on physical metrics, and densities would then strongly correlate with these metrics. We found that densities of stickleback and estuarine-dependent species both correlated with a number of metrics (Table 6). However, after accounting for variance explained by site type, system and visit main effects, most of these correlations disappeared. Note that densities of stickleback and estuarine-dependent species both strongly correlated with connectedness, so the covariation of physical and biological data appear to be mediated primarily by connectivity differences among site types. Nevertheless, it is possible that key physical features influencing fish habitat preference exist at much finer scales than we measured with loggers.

Sensitivity of biological indicators. Two biological indicators appeared strongly influenced by tide gates: Chinook salmon density and more generally, density of estuary-dependent species. For both indicators, SRTs appear to function much more like flap gates than unimpeded channels, more so than would be expected by the linear reduction in connectedness. Because all estuarine-dependent species, including juvenile Chinook salmon, must swim through tide gates

to access upstream areas, connectivity reductions should play a primary role in limiting rearing densities. For Chinook salmon, it is also possible that the combination of lowered connectivity and altered environmental conditions reduced utilization of channel habitat upstream of tide gates. Other studies have found that juvenile Chinook salmon in estuaries are sensitive to water depth and temperature, preferring water at least 1 m deep (Beamer et al. 2005), and less than 15° C (Brett 1952, Brett et al. 1982). Changes to these metrics do not explain why cumulative densities dropped at Fisher Slough after SRT installation (Beamer et al. 2011).

The other biological indicators – stickleback, estuarine neuston, anadromous fish, and nonnative species – were not statistically sensitive to tide gates. Even so, stickleback densities exhibited strong negative correlations with connectedness and water surface elevation and positive correlations with temperature (Table 6), which suggest that high stickleback densities might be diagnostic of poorly connected systems with water quality problems. Indeed, stickleback species are used in indices of biotic integrity to represent species that are tolerant of water quality deficits (Deegan et al. 1992, Seilheimer and Chow-Fraser 2006) in estuary and wetland environments. Furthermore, stickleback contrast with Chinook salmon in that habitat upstream of tide gates can constitute natal habitat.

In addition, anadromous and nonnative species densities exhibited relatively large differences between flap gates and the other two site types, which were swamped by variation in density at flap gates (Fig. 10). Nonnative species were quite rare, totaling of 10 species occurrences at upstream sites (6 at flap sites and 3 at SRTs), so these data should be considered largely preliminary. Anadromous species provided a much richer data set. Although Chinook salmon were included in the anadromous fish taxa, the most abundant anadromous fish were juvenile coho salmon. Across sites, coho salmon were over twice as abundant as Chinook and observed upstream of all but five tide gates (flap or SRTs), absent only in the most saline systems. For coho salmon, losses in connectivity appear only for the extreme case of flap gates. Together, data on anadromous fish and nonnative species suggest that channels upstream of SRTs are more similar to reference sites than flap gated systems.

Management applications. SRTs appear to greatly impact those fish dependent upon rearing in estuaries, but not anadromous fish that pass through them during their outmigration. The passage and upstream habitat criteria for these groups are different. For example, juvenile Chinook do not spawn in creeks upstream of the tide gates in our study. Thus, juvenile Chinook must navigate a tide gate in order to take advantage of upstream habitat. In contrast, coho salmon could originate from adults spawning in creeks upstream of the tide gate. Thus, juvenile densities upstream of tide gates likely represent rearing during outmigration (Miller and Sadro 2003) rather than upstream colonization of habitat.

Given these circumstances, it is worth asking under what conditions is installation of SRTs a prudent alternative to other potential estuary restoration techniques, and what design features should be incorporated. Even in the best of circumstances, SRTs appear to substantially hinder utilization of upstream slough habitat by Chinook salmon and other estuarine-dependent species, and as such are not likely equivalent to dike setbacks, removal, or breaching methods. As such, SRTs appear most useful for systems lacking juvenile Chinook salmon rearing potential but which still have other anadromous species such as coho salmon or steelhead spawning upstream, or for systems that are naturally disconnected (by distance or by channel network) from Chinook salmon migration pathways. In addition, SRTs may also prove useful in removing nuisance species from previously blocked slough habitats. These patterns are suggested in Fig.

10C-D, although our results were inconclusive due to high biological variation. Installation of SRTs does increase tidal elevation and salinity relative to flap gates, so these aspects may have benefits independent of whether they support Chinook salmon and other species. For example, deeper or higher saline waters may help kill noxious aquatic vegetation dependent on freshwater in channel systems.

Our primary biological metrics were fish densities, and an important additional aspect to evaluating whether SRTs might be beneficial in a particular area is the amount of rearing habitat potentially restored. It is possible that for some sites, the benefit of partial reconnection of an extensive channel area trumps the lower densities expected at these sites. In this respect, the relevant metric for calculation is the increase in rearing capacity (number of fish, i.e., density x area) expected by a tide gate installation. To evaluate the utility of a SRT, this value should be compared to the increase in rearing capacity expected by other types of restoration (e.g., breaches, dike setbacks). Because both density and rearing area are expected to be reduced at SRTs compared to other types of restoration, the expectation is that SRTs are likely *at least* an order of magnitude less effective than other type of restoration. However, other constraints may make replacement of flap gates with SRTs valuable for large channel systems.

When managers opt to utilize SRTs for restoration, three additional considerations are the tide gate design, operation, and the monitoring plan. We found that connectedness of over 60% (Table 2) of the tidal cycle was feasible for side-hinged SRTs (Table 2), and we recommend that engineers strive for this standard in design and operation, which can easily be measured using automated loggers. Likewise, SRTs can be constructed with low invert heights to increase the amount of time the SRT is not dewatered while open, and multiple gates or gates set onto a headwall instead of at the end of a culvert can be used to reduce peak velocities to <0.4 m/s (Flagg and Smith 1979, Giannico and Souder 2005) through the gate. SRTs should also have mechanisms (e.g., float settings) that can be changed as necessary in response to adaptive management. Finally, our limited evaluation of SRTs with pet doors suggest that their maintenance challenges may limit their effectiveness. Although pet doors do appear to restore connectivity for anadromous fish, we observed at one site the actual removal of the pet door by strong tidal action.

Given the large sums of money often involved with restoration projects, effectiveness monitoring of projects is often warranted to verify that SRTs function as planned (Bernhardt et al. 2005). Following our temporally extensive study, we recommend designs that incorporate sampling above and below SRTs, preferably before and after installation and in association with comparisons to sites that are not affected by the installation to enable a BACI design. Our studies also identify a number of possible metrics that could be used to monitor SRTs, and reveals that many of these are temporally sensitive (e.g., Chinook salmon densities, Table 5). When funding for monitoring is restricted, low-frequency sampling of these metrics can potentially miss important patterns. In this sense, temporally insensitive metrics such as connectedness are particularly useful for assessing tide gate function. For temporally sensitive metrics, use of automated loggers for monitoring water level and temperature can be useful to provide information over relatively long time periods as long as periodic downloading of data is feasible. Even if the use of loggers is not possible, simple measurements like changes in channel openness may provide a good index of whether the tide gate design is likely improving rearing and passage. For measurement of fish densities, monitoring the entire rearing period is warranted, especially for species like salmon that have temporally variable rearing periods.

Uncertainties and questions for future study. We found substantial variation in physical and biological metrics among SRT and flap gate sites. While some of this variation can be explained by inherent geographic (system) or temporal (visit) variation that could be incorporated into the statistical design, much is likely due to variation in individual design or operation. The SRTs we examined varied from a modified flap fitted with a pet door that opened and closed with tidal fluctuations, to a highly engineered system of upstream floats connected to cams that controlled the simultaneous opening and closing of three side-hinged gates. Likewise, all tide gate sites (flap and SRT) had nonzero values of leakiness. As shown in Figures 7 through 12, individual variation did appear to affect some metrics, resulting in large effect sizes that were not significantly different between groups. This issue was particularly relevant for biological data at flap gate sites, which showed extremely high variation for some fish densities. As a consequence, this study likely is at the low end of the threshold for statistical power for some metrics, primarily due to variation around mean values. Following the rules governing statistical power (Aberson 2010), high variation can be dealt with by adding repeat visits or additional sites. For example, given the mean differences and level of significance for comparisons of flap and SRT means for anadromous and nonnative species (Fig. 10C-D), retrospective statistical power analysis suggests that the number of sites would need to have been nearly tripled or doubled, respectively, to achieve statistical significance. Although a study of that magnitude is unlikely to be done in the future, additional analysis of threshold values of connectivity that allow passage by anadromous species and utilization by nonnative species across flap gates, SRTs and reference sites is warranted.

Looking forward, these findings will likely be increasingly relevant for estuary management. Consideration of SRTs is already quite common in places like the Oregon side of the Columbia River estuary where regulations mandate fish passage, and these deliberations will likely increase as climate change impacts on sea level rise are observed. Sea level rise is predicted to reduce estuary habitat for juvenile Chinook salmon (Kennedy 1990) as slough systems become deeper, more saline, and more simplified. Restoration options will likely become fewer and SRTs will likely be increasingly seen as a compromise to provide habitat opportunity without removing dikes. Effort is needed to predict which channel systems are likely to become high-value restoration sites in the face of sea level rise, and to evaluate the alternatives to SRTs that maintain rearing habitat without compromising adjacent land use values. In addition, entrepreneurial efforts should focus on engineering or restoration designs that combine high connectivity and minimal maintenance.

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¹ This reference can be cited as a chapter appendix through the Federally adopted Puget Sound Chinook Recovery Plan.

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Table 1. Metrics of connectivity used in spatially and temporally extensive studies.

Connectivity metric	Definition	Dimension
Spatially extensive study		
Connectedness	% of time that the channel or tide gate door is open, and water level downstream is not more than 10 cm below the downstream invert	Temporal
Leakiness	% of total tidal flux that is opposite the direction of tidal flow when SRTs gates are closed	Horizontal
Water level	Difference of tidal height (maximum or minimum) and downstream invert	Vertical
Maximum velocity	Maximum velocity (m/s) measured at site during ebb (out) and flood (in)	Horizontal
Temporally extensive study		
Tidal muting (m)	Downstream - upstream difference in maximum higher high water (MHHW)	Vertical
Effective MHHW (m)		Vertical
Tidal muting (%)	% of downstream MHHW that is muted (downstream-upstream MHHW)	Vertical
% channel width open	% of channel width that can pass water	Horizontal
% time channel is open	% of time that the channel or tide gate door is open	Temporal
% time fish can swim upstream	% of time channel or tide gate door is open and tide is flooding	Temporal

Table 2. Sites, listed from North to South and their attributes, including site type (SRT, Flap, or Reference), the geographic system, number of SRT and passive gates (* = side-hinged gates, all others are flap gates), dimensions of the monitored culvert, total vertical cross-sectional area of gated channel (SRT and passive gated culverts combined), downstream and upstream invert elevation (NAVD88 GEOID09 Mean Low Water), mean connectedness (see text), and the upstream limit of tidal flux above SRTs. M = missing data, ¹ = Side-hinged gate, ² = Top-hinged gate, ³ = Pet door on gate, ⁴ = Pump house present that actively pumps water from upstream channel, and ⁵ = measurements are based on dimensions of the gate on its headwall, as it has no culvert.

Site name	Site Type	System	Number of SRT Gates	Number of Passive Gates	Monitored Culvert Opening Diameter or Width x Height (m)	Total Area of Gated Channel (m ²)	Down-stream Invert Elevation (m) ²	Up-stream Invert Elevation (m ²)	Connect- edness (mean)	Up- stream Tidal Limit (m)
McElroy Sl.	SRT ¹	Samish/Padilla Bay	1	3	1.8 x 1.8	13.0	0.31	0.40	0.62	1836
Edison Sl.	SRT ¹	Samish/Padilla Bay	1	6	1.84 x 1.22	20.3	0.73	0.79	0.50	3799
Edison Flap	FLAP ^{2,4}	Samish/Padilla Bay		3	1.21	3.4	0.15	0.20	0.05	
N. Indian Sl.	REF	Samish/Padilla Bay							0.99	
N. Fornsby	SRT ¹	Swinomish Channel	1	1	1.3 x 1.2	3.1	-0.16	-0.24	0.19	2714
Higgins Sl.	FLAP ²	Swinomish Channel		5	1.51	9.0	-0.47	-0.20	0.14	
S. Fornsby	SRT ¹	Swinomish Channel	1	1	1.29 x 1.21	3.1	0.07	0.11	0.18	764
Old Bridge	REF	Swinomish Channel							0.80	
Fisher	REF	Skagit River							1	
Fisher Sl.	SRT ¹	Skagit River	3	2	3.35 x 2.67 ⁵	27.6	1.31 ⁵	1.31 ⁵	0.77	1584
Big Ditch	FLAP ²	Skagit River		7	2.82	43.7	-0.61	-0.37	0.25	
Frye Cr.	FLAP ^{2,4}	Chehalis River		2	1.66	4.3	-0.24	0.52	0.07	
Alder Cr.	SRT ¹	Chehalis River	1	1*	1.88 x 1.8	6.8	-0.15	-0.15	0.51	1073
Mill Cr.	SRT ¹	Chehalis River	1	2*	1.23 x 1.12	4.1	0.12	0.12	0.52	927
Devonshire Cr.	SRT ¹	Chehalis River	1	1*	1.83 x 1.81	6.6	0.92	0.92	0.62	1690
Charley Cr.	REF	Chehalis River							0.76	
Vera Sl.	SRT ^{1,3}	Young's Bay	1	1	1.55 x 1.55	4.8	0.21	0.21	0.29	3667
N. Hansen Cr.	FLAP ²	Young's Bay		1	1.23	1.2	-0.56	-0.13	0.23	
S. Hansen Cr.	SRT ^{2,3}	Young's Bay	1	1	1.24	2.4	-0.50	-0.07	0.14	M
S. Clatsop Sl.	REF	Young's Bay							1	

Table 3. Species captured in beach seines, their class(es) if included in a species group, and the frequency with which it was captured (at different sites, upstream or downstream sampling locations, or visits).

Species	Scientific name	Species class(es)	Frequency
Three-spine stickleback	<i>Gasterosteus aculeatus</i>		92
Staghorn sculpin	<i>Leptocottus armatus</i>	Estuarine-dependent	49
Coho salmon	<i>Oncorhynchus kisutch</i>	Anadromous	47
Chinook salmon	<i>O. tshawytscha</i>	Estuarine-dependent, Anadromous	42
Prickly sculpin	<i>Cottus asper</i>		38
Chum salmon	<i>O. keta</i>	Estuarine-dependent, Anadromous	28
Peamouth chub	<i>Mylocheilus caurinus</i>		23
Shiner perch	<i>Cymatogaster aggregate</i>	Estuarine-dependent	22
Starry flounder	<i>Platichthys stellatus</i>	Estuarine-dependent	18
Surf smelt	<i>Hypomesus pretiosus</i>	Estuarine-dependent	15
Cutthroat trout	<i>O. clarkia</i>	Anadromous	9
Snake prickleback	<i>Lumpenus sagitta</i>	Estuarine-dependent	4
Largescale sucker	<i>Catostomus macrocheilus</i>		3
Pacific herring	<i>Clupea pallasii</i>	Estuarine-dependent	3
Dungeness crab	<i>Metacarcinus magister</i>	Estuarine-dependent	3
American shad	<i>Alosa sapidissima</i>	Anadromous, Nonnative	3
Yellow perch	<i>Perca flavescens</i>	Nonnative	3
Bullfrog tadpole	<i>Rana catesbeiana</i>	Nonnative	3
Rainbow trout/steelhead	<i>O. mykiss</i>	Anadromous	2
Smallmouth bass	<i>Micropterus dolmieu</i>	Nonnative	2
Pacific sand lance	<i>Ammodytes hexapterus</i>	Estuarine-dependent	2
Pumpkinseed	<i>Lepomis gibbosus</i>	Nonnative	2
Shrimp		Estuarine-dependent	2
Eulachon	<i>Thaleichthys pacificus</i>	Anadromous	1
Crescent gunnel	<i>Pholis laeta</i>	Estuarine-dependent	1
Bluegill	<i>Lepomis gulosus</i>	Nonnative	1
Grass pickerel	<i>Esox americanus</i> <i>vermiculatus</i>	Nonnative	1
Rough-skin newt	<i>Taricha granulosa</i>		1
Speckled dace	<i>Rhinichthys osculus</i>		1
Unknown gadoid	<i>Gadidae spp.</i>	Estuarine-dependent	1

Table 4. Fish sampling design used in the temporally extensive study. All channels with a tide gate are denoted as treatment, while channels lacking any such structures are noted as reference. Beach seine sites are abbreviated as seines.

Area	Type	Number & type of sampling sites		# of sets per sampling site per day		Sampling period
		Upstream	Downstream	Upstream	Downstream	
Fisher	Treatment	7 seine	1 seine	1	2	February-June ¹
	Reference	1 fyke	1 seine	1	2	
S. Fornsby	Treatment	2 seine	1 seine	1	5	February-August ²
	Reference	1 fyke	1 seine	1	3	
McElroy	Treatment	3 seine	3 seine	1	1	April-June ³
S. Fork estuary (3 sites)	Reference	1 fyke per reference	1 seine per reference	1	2	February-August
N. Fork estuary (3 sites)	Reference	1 fyke per reference	1 seine per reference	1	2	February-August

¹Sampling went through August in 2009 and July in 2010.

²Sampling periods in 2004 and 2005 were March-June and February-June, respectively.

³In 2011, sampling period was February-June.

Table 5. Effects of site type (Flap (F), SRT (S), or Reference(R)), system, visit or two-way interactions on physical and biological variables. Values indicate p-values (boldface indicate $p < 0.05$, italics indicate $0.05 < p < 0.1$) based on a general linear model on upstream data with visit used as repeated measure. Pairwise LSD post-hoc comparisons are diagrammed in the third column, with site types ranked from lowest to highest from left to right, and connected by lines below or above letters to show types that do not significantly differ from each other, or separated by multiple spaces to indicate significant pairwise comparisons.

Variable	Site type	Post-hoc	System	Visit	Site type* System	Site type* Visit	System* Visit
Connectedness	<0.001	F S R	0.042	>0.1	0.044	>0.1	<i>0.082</i>
Leakiness	0.009	<u>R S</u> F	<i>0.051</i>	---	0.029	---	---
Water level (open)							
Min	>0.1	<u>S R</u> F	>0.1	0.021	>0.1	>0.1	>0.1
Max	>0.1	<u>S F R</u>	>0.1	>0.1	>0.1	>0.1	>0.1
Velocity (open)							
Max in	>0.1	<u>F R S</u>	>0.1	---	>0.1	---	---
Max out	>0.1	<u>S R F</u>	>0.1	---	>0.1	---	---
Surface elevation (closed)							
Min	0.025	F <u>S R</u>	0.046	<i>0.091</i>	>0.1	>0.1	>0.1
Mean	0.007	F S R	>0.1	0.010	>0.1	>0.1	>0.1
Max	0.002	F <u>S R</u>	>0.1	0.028	>0.1	>0.1	>0.1
Salinity (closed)							
Min	>0.1	<u>R S F</u>	0.008	0.013	0.036	<i>0.059</i>	0.042
Mean	>0.1	<u>R F S</u>	<0.001	>0.1	0.036	>0.1	>0.1
Max	>0.1	<u>F R S</u>	<0.001	>0.1	>0.1	>0.1	>0.1
Temperature (closed)							
Min	0.012	R <u>S F</u>	0.034	<0.001	<i>0.089</i>	0.029	<0.001
Mean	<i>0.062</i>	<u>R F S</u>	0.003	<0.001	>0.1	>0.1	<0.001
Max	>0.1	<u>F R S</u>	>0.1	<0.001	>0.1	>0.1	>0.1
Chinook	0.028	<u>F S</u> R	0.013	<i>0.068</i>	>0.1	>0.1	0.001
Stickleback	0.740	<u>R S F</u>	>0.1	0.014	>0.1	>0.1	>0.1
Estuarine spp	0.015	<u>F S</u> R	<i>0.066</i>	>0.1	>0.1	>0.1	>0.1
Estuarine neuston	>0.1	<u>R F S</u>	<i>0.060</i>	---	>0.1	---	---
Anadromous spp	>0.1	<u>F R S</u>	>0.1	>0.1	>0.1	>0.1	>0.1
Nonnative spp	>0.1	<u>S R F</u>	<i>0.082</i>	>0.1	<i>0.063</i>	>0.1	>0.1

Table 6. Correlations between physical metrics and either biological metrics (Data) or their unstandardized residuals (Res.) from the GLMs. Significant correlations ($p < 0.05$) are in boldface.

Variable	Chinook		Stickleback		Estuarine		Neuston		Anadromous		Nonnative	
	Data	Res.	Data	Res.	Data	Res.	Data	Res.	Data	Res.	Data	Res.
Connectedness	0.21	-0.02	-0.28	-0.01	0.39	-0.01	-0.19	0.07	0.23	-0.03	-0.06	0.04
Leakiness	0.03	-0.03	-0.01	0.14	-0.30	0.01	-0.22	-0.04	-0.10	-0.09	-0.06	0.08
Water level (open)												
Min	0.10	-0.06	-0.14	-0.01	0.05	-0.06	-0.17	-0.12	0.19	0.20	0.18	-0.03
Max	-0.09	0.11	-0.44	-0.28	0.28	-0.04	0.15	-0.02	0.09	0.11	0.07	-0.16
Velocity (open)												
Max in	0.20	0.06	-0.06	0.03	0.09	0.03	-0.22	-0.16	0.25	0.21	-0.02	-0.20
Max out	0.05	-0.17	0.27	0.02	0.13	-0.16	0.01	0.24	-0.28	-0.27	0.27	0.10
Surface elevation (closed)												
Min	0.16	-0.12	-0.18	0.11	0.13	-0.03	-0.19	0.02	0.13	-0.06	-0.13	0.11
Mean	0.20	-0.13	-0.29	0.10	0.31	-0.06	-0.11	0.08	0.16	-0.08	-0.15	0.08
Max	0.17	-0.15	-0.31	0.11	0.36	-0.07	-0.13	0.06	0.16	-0.06	-0.14	0.05
Salinity (closed)												
Min	-0.11	-0.05	0.30	0.12	-0.18	-0.02	0.22	-0.05	-0.24	-0.05	0.04	-0.01
Mean	0.11	-0.05	0.27	-0.02	-0.10	-0.05	0.02	0.20	-0.08	-0.06	-0.10	-0.03
Max	0.16	-0.05	0.23	-0.06	-0.12	-0.01	-0.02	0.24	0.01	-0.01	-0.21	-0.01
Temperature (closed)												
Min	-0.08	0.04	0.26	0.03	-0.07	0.02	0.19	-0.22	0.08	-0.04	0.12	-0.05
Mean	0.03	-0.02	0.28	0.02	-0.05	0.00	-0.05	0.09	0.15	-0.02	-0.05	-0.02
Max	0.11	-0.08	0.30	0.05	-0.03	-0.06	-0.10	0.26	0.17	-0.06	-0.14	0.02

Table 7. Cross correlations of physical variables measured in the temporally extensive study. All correlations are significant ($p < 0.05$).

	Tidal muting (m)	Tidal muting (%)	Effective MHHW (m)	Channel wid. open (%)	Time doors open (%)	Cum. density ratio
Tidal muting (%)	0.96					-0.79
Effective MHHW (m)	-0.95	-0.93				0.75
% channel width open	-0.87	-0.88	0.93			0.87
% Time doors open	-0.98	-0.92	0.93	0.84		0.65
% Time fish can swim upstream	-0.95	-0.85	0.86	0.75	0.96	0.56

Figure 1. Location of study sites by type (circle = flap, square = SRT, and triangle = reference) in five systems in estuaries across the Pacific Northwest.



Figure 2. Self-regulating tide gates (A-J) and examples of a flap gate (K, North Hansen) and a reference site at low tide (L, Charlie Creek) used in the study design. SRTs are ordered from North to South as in Table 2. Photo credits to Jason Hall, except A (Brittany Jones), B (Oscar Bunting), C and E (Dana Rudy), D (Todd Mitchell), H (Kirsten Weinmeister), and I (Curtis Roegnor).



Figure 3. Physical measurements collected at sites. This figure depicts a cross section of an SRT site with gate and rectangular culvert (with supporting dike fill material or bridge construction removed) connecting an “upstream” channel with its estuary “downstream”. Measurements are: 1) angle logger recording whether tide gate was open or closed, 2) and 3) stand pipes for loggers collecting downstream and upstream water level, salinity, and temperature data, respectively, 4) invert elevation of culvert measured at low tide, and 5) velocity probe that measured water flow and direction as well as culvert water level (dotted line). Flap gates and reference sites were also measured for these attributes as appropriate.

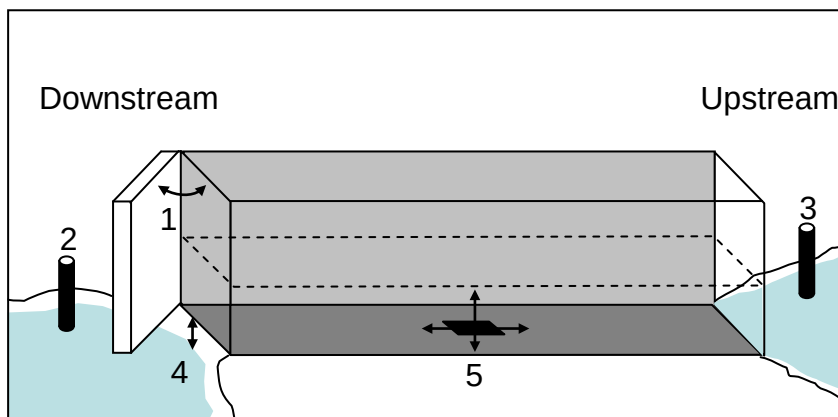


Figure 4. Water velocity (thin line, right axis) and culvert water level (thick line, left axis) within a nonleaky (A) or leaky (B) SRT over the course of a tidal cycle, including the period of time the gate was closed (gray).

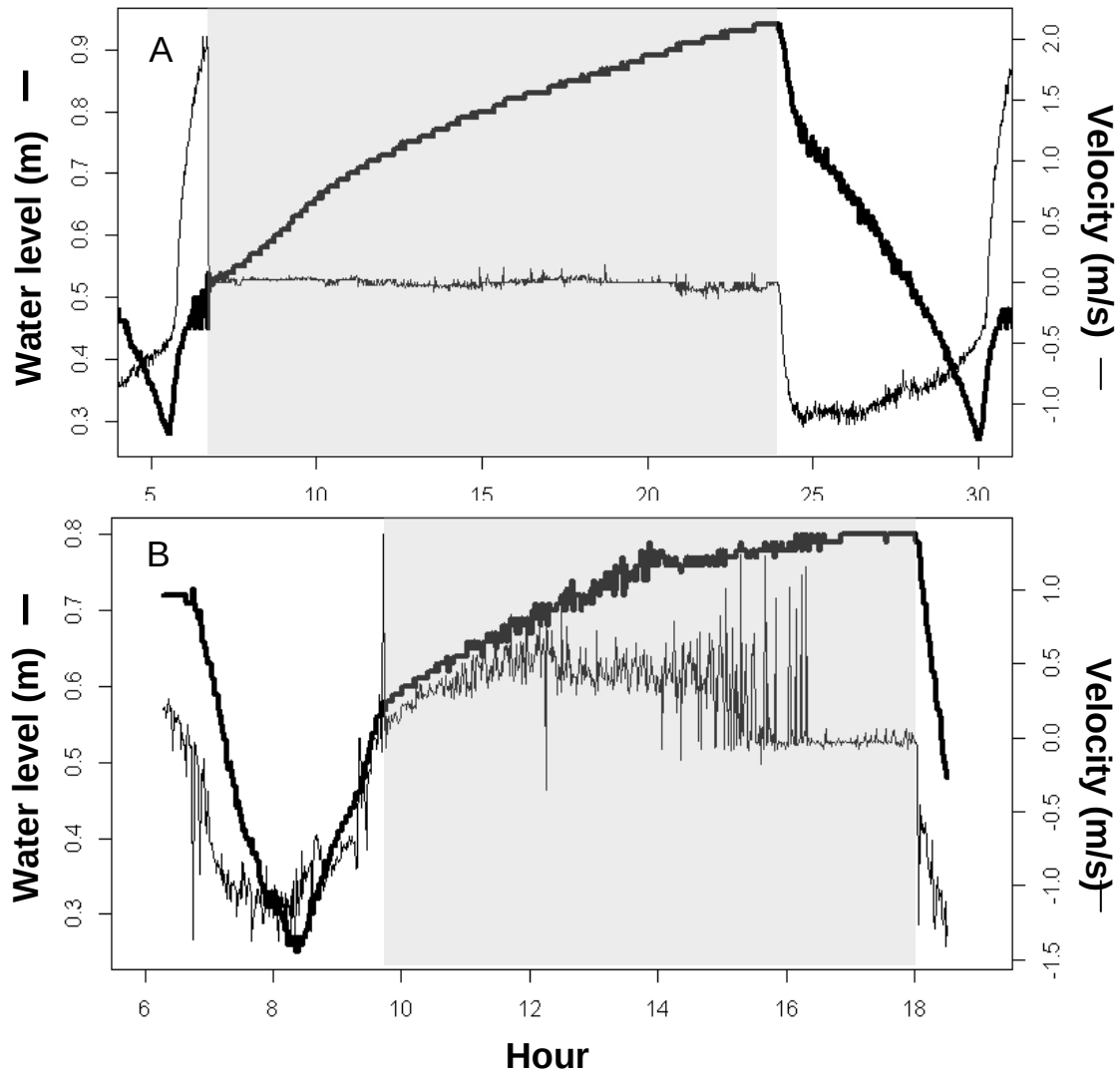


Figure 5. Sites used in the temporally extensive study. Boxes are SRT sites and triangles are reference sites.

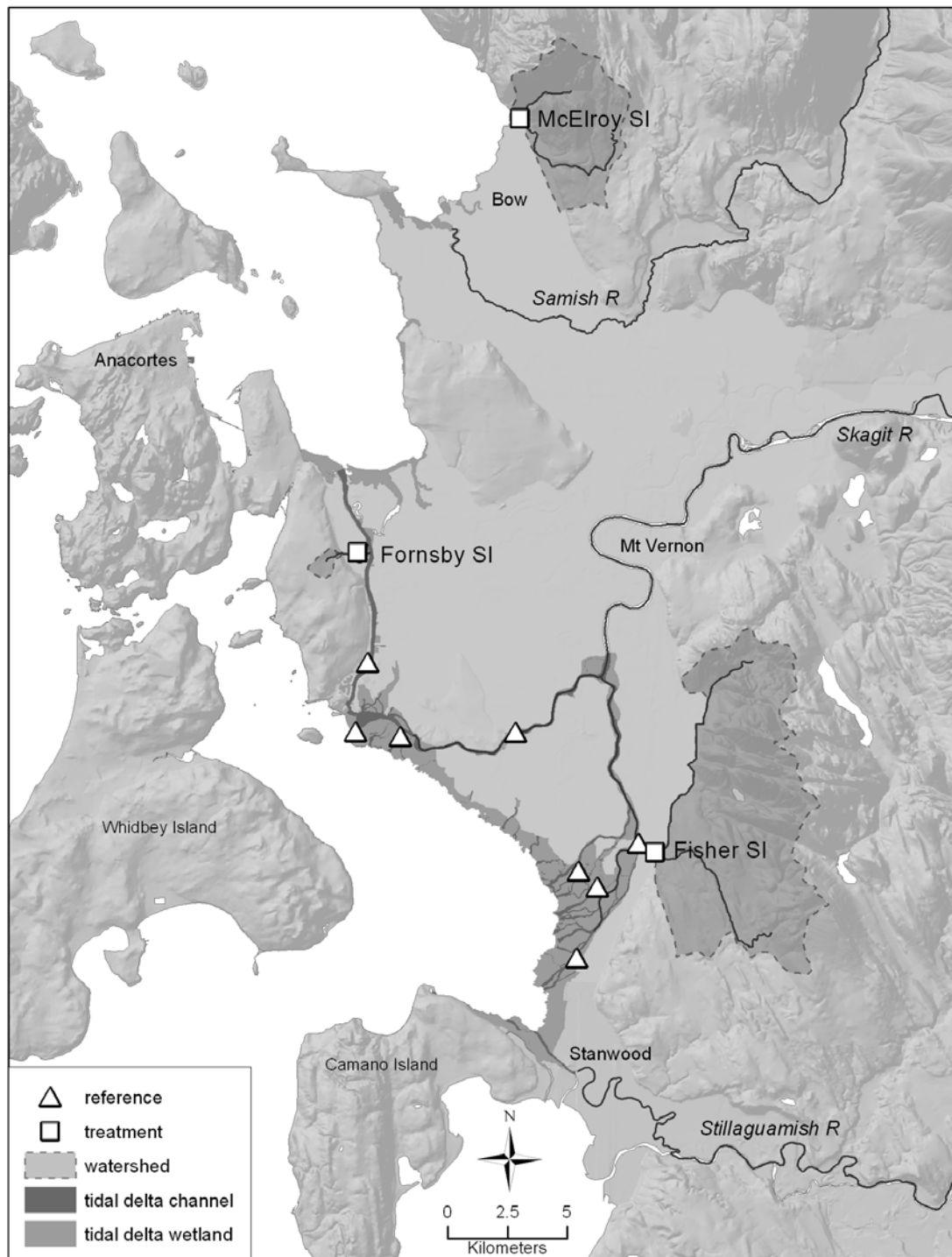


Figure 6. Examples of how water level, temperature, and salinity vary below (thin lines) and above (thick lines) across a single day at three different site types within one system (Samish/Padilla Bay). Grayed areas indicate periods of time when tide gates were closed.

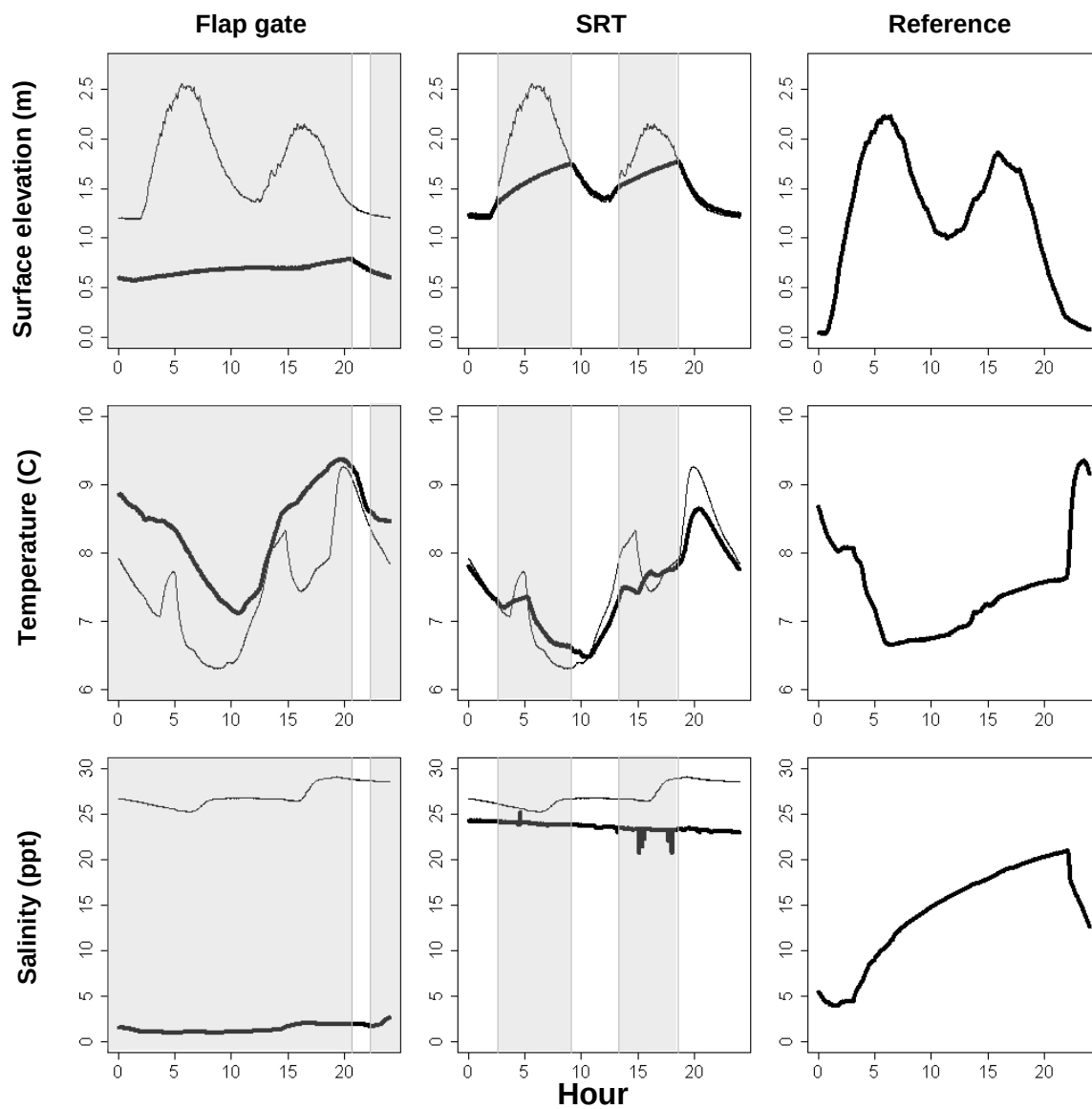


Figure 7. Metrics influencing connectivity at each site type. A) connectedness (proportion of time site is accessible and inside-outside water level < 10 cm), B) maximum (filled diamonds) and minimum (filled circles) water level relative to invert height downstream, C) leakiness (see text for definition), and D) maximum velocity of water moving out of (positive scores, filled diamonds) or into (negative scores, open diamonds) channel. Error bars indicate ± 2 standard errors.

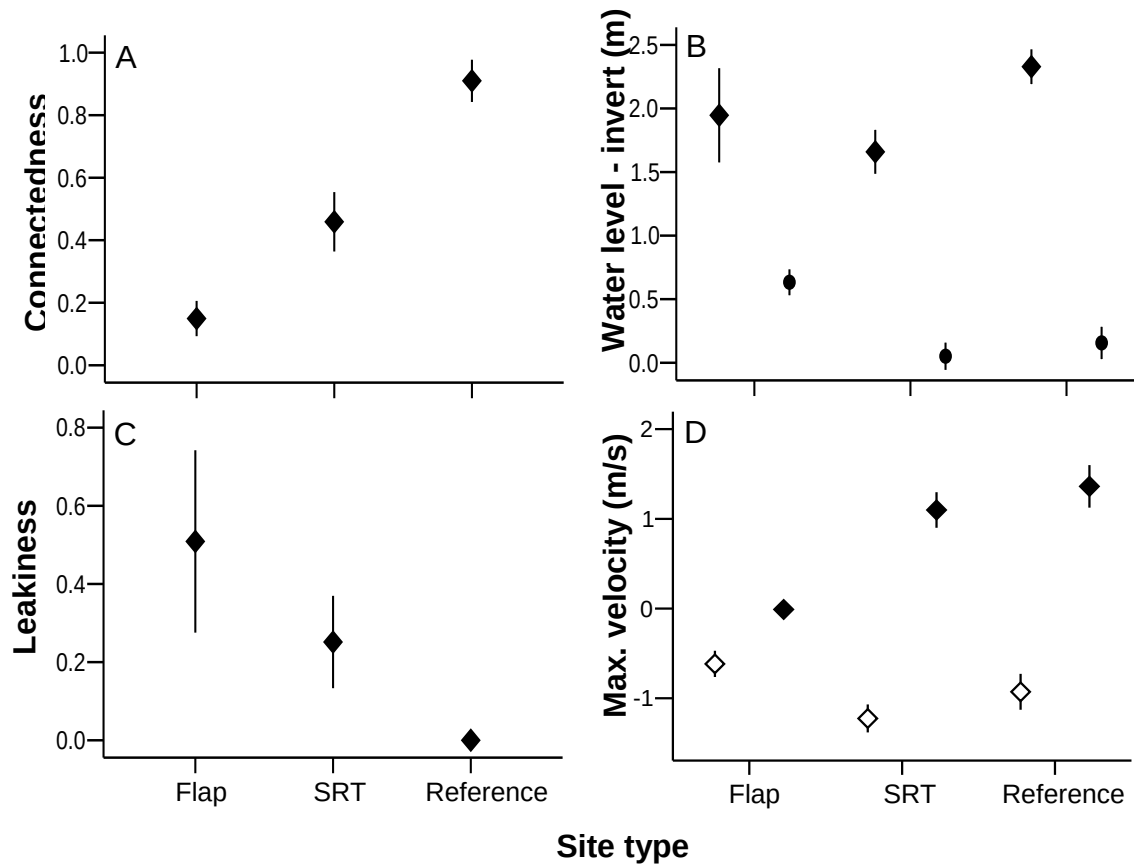


Figure 8. Mean values of average, maximum, and minimum water level, salinity, and temperature by site type downstream (open diamonds) and upstream (filled diamonds) of tide gates. Reference sites were measured at only one place, and indicated as upstream. Average values are represented by the diamonds, and maximum and minimum are indicated by the endpoint of the error bar.

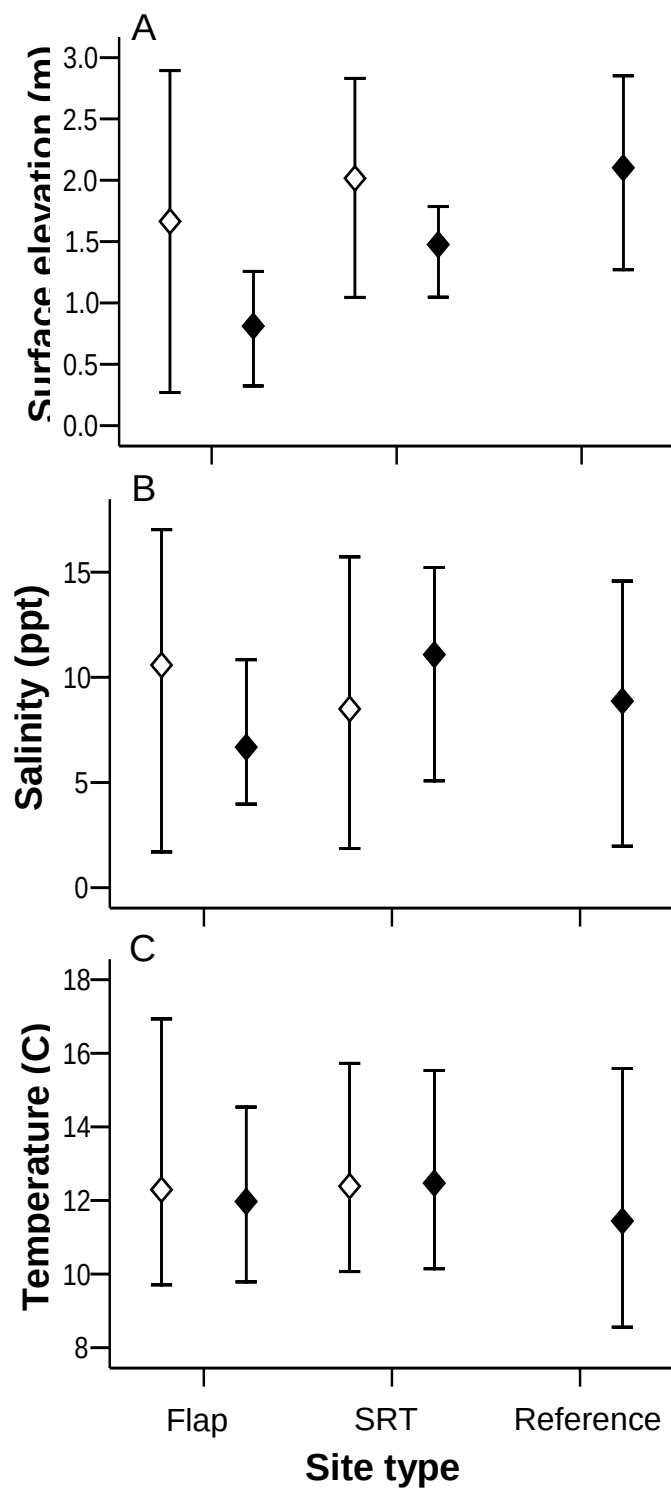


Figure 9. Mean differences (± 2 standard errors) in relative density of A) Chinook salmon and B) three-spine stickleback upstream (filled diamonds) and downstream (open diamonds) of flap gates, self-regulating tide gates (SRT), and reference sites. Densities for a given site are represented relative to its reference site and are log base-10 transformed (see methods).

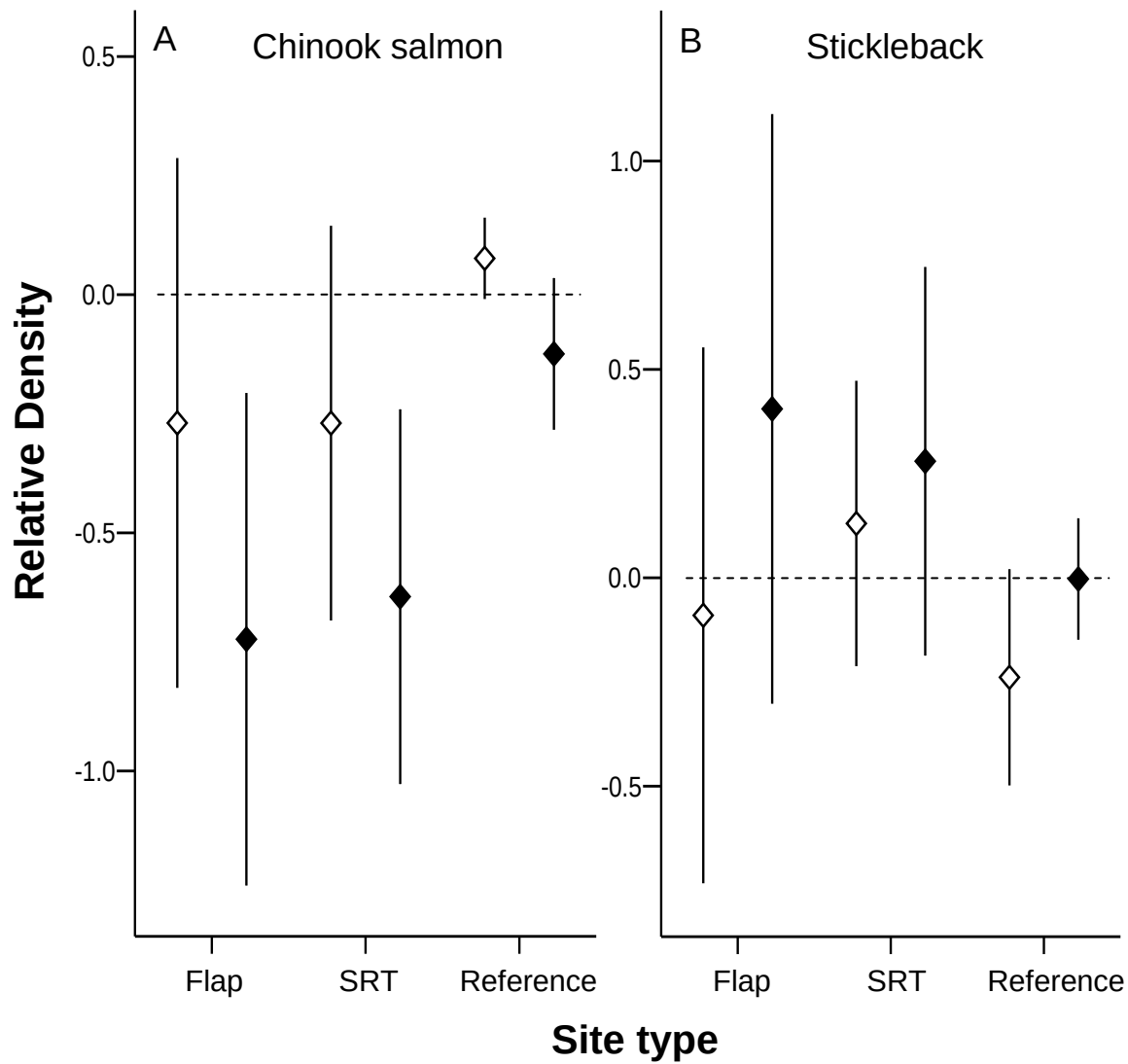


Figure 10. Mean differences (± 2 standard errors) in relative density of A) estuarine dependent species B) estuarine neuston, C) anadromous species, and D) nonnative species upstream (filled diamonds) and downstream (open diamonds) of flap gates, self-regulating tide gates (SRT), and reference sites. Densities for a given site are represented relative to its reference site and are log base-10 transformed (see methods).

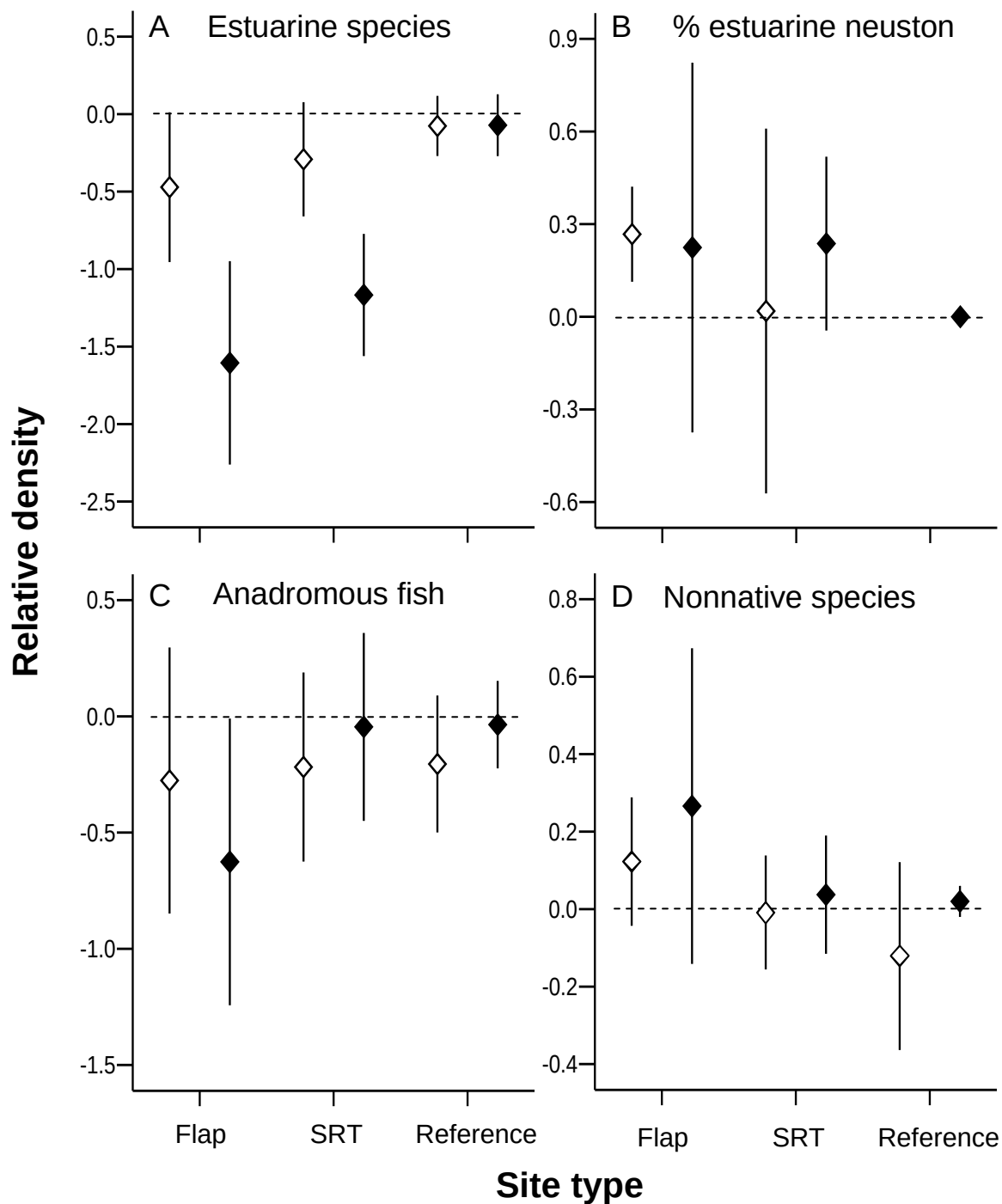


Figure 11. Ratio of cumulative Chinook salmon density (inside/outside) at A) Fisher Slough monitoring sites, B) S. Fornsby monitoring sites, C) McElroy Slough, and D) Skagit estuary reference sites (SF = South Fork, NF = North Fork) , referenced by year and/or variation in operation. Dark gray and white bars are treatment and reference sites, respectively. In A and B, Man. = Manual, S-hinge = Side-hinge, and Ref. = Reference. Error bars are ± 1 standard error. Note that the range changes on the y-axis among panels.

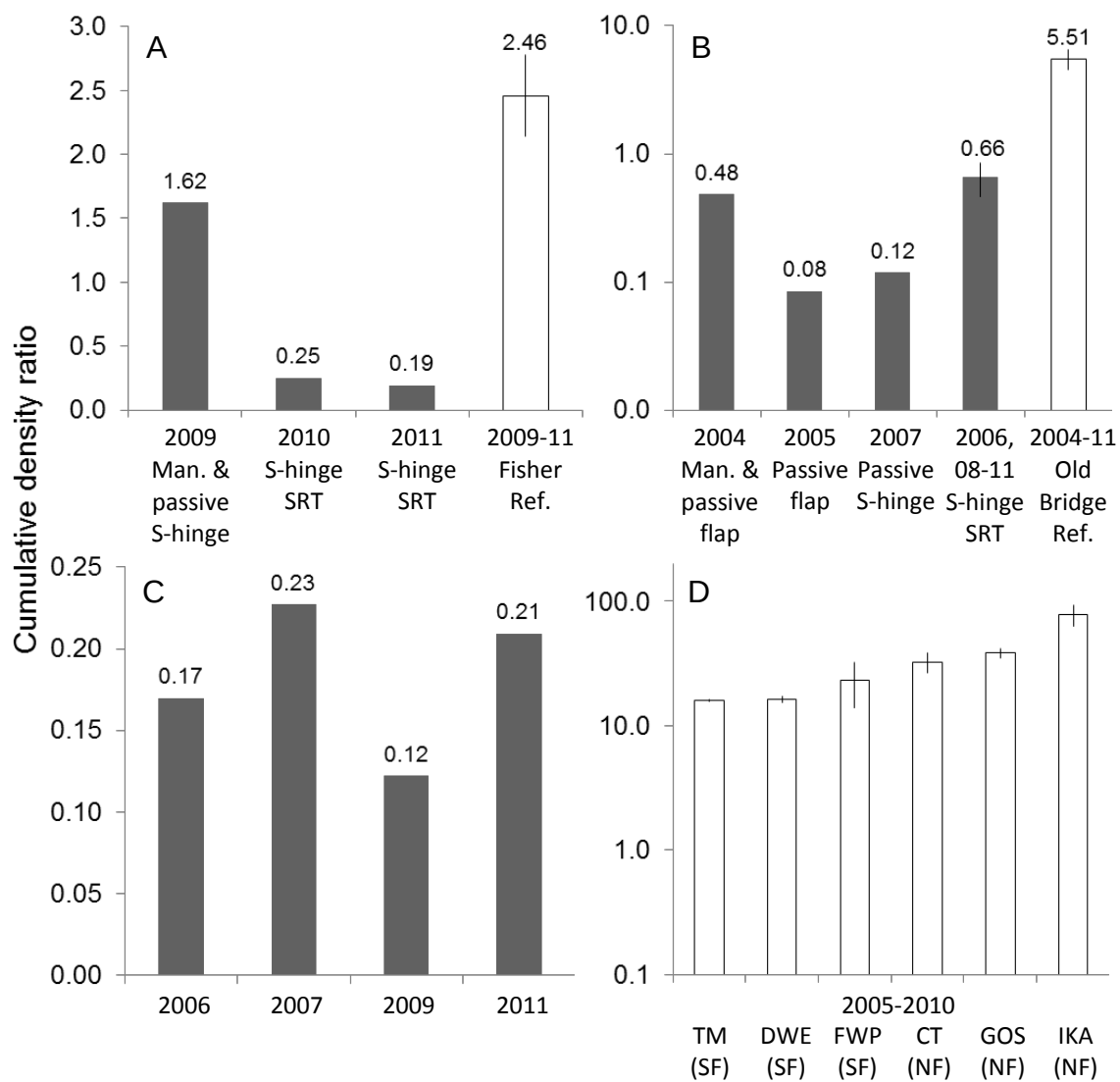


Figure 12. Relationships between cumulative Chinook salmon density (inside/outside) and A) proportion of the channel that is open B) effective mean high high water (MHHW) above sea level (NAVD88), for sites varying in operation or type (treatment versus reference).

