Tide Gates in the Pacific Northwest

Operation, Types, and Environmental Effects

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Oregon Sea Grant • ORESU-T-05-001

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This research and publication were funded by the National Sea Grant College Program of the U.S. Department of Commerce's National Oceanic and Atmospheric Administration, under NOAA grant number NA76RG0476 (project number R/HBT-07-PD), and by appropriations made by the Oregon State legislature. The views expressed herein do not necessarily reflect the views of any of those organizations.

Sea Grant is a unique partnership with public and private sectors, combining research, education, and technology transfer for public service. This national network of universities meets the changing environmental and economic needs of people in our coastal, ocean, and Great Lakes regions.

Support for this project also came from the Coos Watershed Association.

Credits

Editing and layout: Sandy Ridlington
Illustrations: Jon A. Souder
Photographs: Coos Watershed Association

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Acknowledgments

We would like to thank Douglas Tave, who did most of the groundwork and literature search for this project. His assistance was of extraordinary value and we could not have completed this report without him.

We also want to acknowledge the following people for providing information, assistance, and advice and for sharing their knowledge, experiences, and ideas with Douglas and us—they were instrumental in the completion of this report: John Abenroth, Ken Bates, Eric Beamer, Ken Buchanan, Douglas Bulthuis, Barbara Butler, John Coles, Charlie Corrarino, Todd Cullison, Joel Davis, Richard Eliasen, Richard Felley, Don Finlay, Melissa Gildersleeve, Denny Hach, Jeff Haltiner, Erin Hanson, Mary Holbert, Al Jonsson, Jane Kelly, Leo Kuntz, Beth Lambert, Deb Merchant, Eugene Niles, Don Porior, Ed Reiner, Don Reynolds, Ron Rozsa, Jim Scheller, Frank Stang, Thomas J. Steinke, Alan Thomson, Colin Wagoner, and Allan Whiting.

Charles Corrarino, Paul Heikkila, Kim Jones, and Charles Simenstad reviewed an early version of this report and provided comments and advice that helped improve it significantly. Any of the shortcomings of the report remain the responsibility of the authors.

Funding for this project was provided by Oregon Sea Grant, under project number R/HBT-07-PD, Index NA650B.

Introduction

Historically, wetlands have been considered an impediment to efficient and productive land use, and, therefore, they have been drained and manipulated for different purposes. In Europe, the use of dikes and tide gates to convert estuarine wetlands into agricultural lands and to allow urban development on low-lying coastal zones began in the seventh century and was common practice by the eleventh and twelfth centuries (Daiber 1986). This type of land conversion has occurred in other continents as well and is the single greatest reason for the destruction of wetlands worldwide (Middleton 1999).

Another important reason for draining wetlands has been public health protection. For many centuries, populations of mosquitoes and other insects that breed in wetlands have been controlled, with different degrees of success and a variety of environmental consequences, by drying up tidal marshes and swamps. The available evidence indicates that mosquito control by wetland filling and draining began over 2,100 years ago in the Italian peninsula (Doody 2001). In North America, these kinds of mosquito-control practices were first implemented in some southeastern states of the United States in the early nineteenth century (Doody 2001) and were adopted in some northeastern states after the Civil War, as homeward-bound soldiers introduced malaria to the region (Dreyer and Niering 1995). For example, in Connecticut the disease reached epidemic proportions within a relatively short time, and all types of wetlands were destroyed to reduce the populations of Anopheles mosquitoes.

As the threat of malaria was eliminated in the northeastern United States, control efforts targeted other species of mosquitoes that represented a public nuisance, and hundreds of kilometers of ditches were hand dug during the Great Depression to drain many wetlands dry. Even to this date, tidal marsh regulation for insect control is still common practice in some parts of the southeastern United States. Florida, for example, manages 16% of its east coast marshes for mosquito and sand fly control (Montague et al. 1987). It is worth pointing out that this old practice continues despite evidence that indicates it may be not only ineffective but also counterproductive. This is because it may create a much less manageable pest-control situation while eliminating important estuarine resources (Portnoy 1984). Dikes, and their associated tide control gates, have not effectively reduced mosquito breeding grounds in many areas. Instead, they have replaced brackish-water mosquito species with freshwater mosquito species (Dreyer and Niering 1995).

Along the coast of northwestern North America during the past two hundred years, dikes and levees have been built to drain tidal wetlands, both to convert them into agricultural land and to protect flood-prone areas. Between 1780 and 1980, California experienced the loss of 91% of its wetlands, coastal and interior; Oregon 38%; and Washington 31% (Dahl 1990). However, in the past two decades the encroachment of urban and industrial land uses has become an increasingly common cause of wetland loss in coastal areas. Among estuarine wetlands, tidal marshes close to seaports and urban centers have been particularly vulnerable to conversion, with losses of 50% to 90% reported for many estuaries in Oregon and Washington (NRC 1996). Many of these marshes have been isolated from the adjacent estuaries by dikes (Frenkel and Morlan 1991) and in some cases completely or partly filled in to accommodate a variety of land uses (agricultural, recreational, residential, industrial). For example, in areas such as Coos Bay, Oregon, almost 90% of tidal marshes have been permanently lost to dikes and landfills (Hofnagle et al. 1976), and in parts of Puget Sound, Washington, over 95% of tidal wetlands have been lost (Gregory and Bisson 1997).

Tide gates allow freshwater to flow into the estuaries but prevent the upstream movement of brackish estuarine waters. The use of dikes and tide gates has enabled farmers and coastal communities to convert coastal wetlands into agricultural and grazing fields, and flood-prone lands into urban zones. These considerable changes in river-estuary and in river-floodplain connectivity have some undesirable physical, chemical, and biological side effects. This report examines some of those effects. However, a detailed description of estuarine ecology is beyond the scope of this publication, and details about various aspects of estuarine ecology can be found in a variety of textbooks. Simenstad's report about the ecology of estuarine channels of the Pacific Northwest coast provides a wealth of information on this subject (Simenstad 1983).

Although each estuary is unique, the primary driving force in these systems is the tidally influenced mixing of waters of dissimilar salinities. Because fresh and salt water have different densities and temperatures, the denser incoming salt water tends to dive beneath the outgoing freshwater and may create a wedge that moves along the bottom, up the estuary, and toward the river. The presence, strength, and shape of the salt wedge are determined by the river flow, geomorphology of the estuary, season, stage of tidal month, and so on (Simenstad 1983; Geyer and Signell 1992; Largier 1992). The area of contact and partial mix between freshwater and salt water is known as “front” (Largier 1992, 1993). Fronts are mobile zones with increased levels of biological productivity. Productivity is high because the water mixing and circulation patterns keep a large amount of organic detritus and nutrients, of both river and marine origin, in suspension. The fact that estuaries function like nutrient traps allows the development of very complex food webs that include a great diversity of algae, invertebrates, fish, birds, and mammals (Simenstad 1983; Shreffler et al. 1992; Largier 1993). The deposition of some of the suspended nutrients and organic matter, in turn, maintains a diverse bottom community (that is, benthos) (Largier 1993).

The negative ecological consequences of diking and regulating estuarine wetlands with flood boxes and tide gates have received relatively little attention. It has been only a few years since the effects of these structures on salmon populations became a concern for management agencies and nongovernmental organizations. Whereas the effects of dams, roads, culverts, and water diversion projects on migratory species of fish have been the focus of many studies and their construction and operation require considerable mitigation actions, there is scarce information on—and consequently a poor understanding of—the problems caused by dikes and tide gates on fish. The notion that tide gates interfere with fish migration has encouraged the development of the so called “fish-friendlier” gate designs. Unfortunately, information on the effectiveness of such alternative designs is limited and most often available only from the tide gate manufacturing companies.

This report is an attempt to address some critical information gaps regarding the effects of dikes and tide gates on coastal ecosystems and fisheries resources. The authors have identified the information needs during their work with landowners, community organizations, and resource management agencies and through a compilation and summary of information on dikes and tide gates derived from an extensive literature review. They illustrate the characteristics of traditional tide gate designs and their operation, explain the environmental effects of dikes and tide gates, describe new tide gate designs—including those that are considered fish friendlier—and identify current knowledge gaps that may guide future research directions. Included at the end of the report are a brief directory of manufacturers (Appendix 1) and a summary of relevant U.S. and Canadian laws and regulations (Appendix 2).

Dikes, Flood Boxes, and Tide Gates

Dikes are elevated earthen embankments raised along tidally influenced channels in estuaries and coastal sections of rivers or along channel systems that drain wetlands. Their primary function is to keep low-lying lands from being flooded during either high tides or periods of high river discharge. To control the flow of upland water into diked estuarine zones or river reaches and to prevent estuarine intrusion behind those dikes, structures known as flood, or tide, boxes are used. A flood box may be as simple as a single culvert running through a dike wall or as complex as a concrete structure that is the size of a small bridge and includes two or more culverts, deflecting wing walls, and pilings, both up and downstream (figure 1).

In all cases, doors or lids are attached to the discharge ends of the culverts to control the flow of water. These doors are commonly referred to as flap gates or tide gates (figure 2). Tide gates close during incoming (flood) tides to prevent tidal waters from moving upland, and open during outgoing (ebb) tides to allow upland waters to flow through the culvert and into the estuary side of the dike (Charland 1998; Thomson and Associates 1999).

Tide gates can be placed at the mouth of streams or small rivers, where the estuary begins. However, in the Pacific Northwest they are most often installed where tidal nonriverine channels that drain marshes, tributary streams, or field drainage ditches connect to sloughs (C. Simenstad, University of Washington, personal communication) (figure 3).

In some large basins, primarily those characterized by snowmelt-driven freshets of the main stem (for example, the Fraser River), the flood boxes on the mouth of tributaries and sloughs might be equipped with mechanical pumps that control the water level on the upland side of dikes while tide gates are shut. Tide gates in such systems remain closed during early spring to keep water in the main channel from flooding or backlogging the lower reaches of its smaller tributaries (Thomson and Associates 1999).

Tide Gate Operation

There are many different types of tide gates, but the most common configurations include either top-hinged or side-hinged lids installed on the downstream ends of culverts. Tide gates open and close as the result of water level differences between the downstream and the upstream sides of the gate. Because a tide gate rests against the mouth of a culvert (or against ridges, if it is placed inside the culvert), it can open only in one direction, away from the culvert. Such unidirectional movement of the lid allows water to flow in only one direction, downstream, and prevents backflow during flood (high) tides.

A tide gate opens during ebb (low) tides, when water pressure on its upstream side exceeds both the pressure of water on its downstream side and the gate's own "restorative" force. This force (also known as effective weight) is caused by the effect of gravity on the gate and is responsible, in the absence of water pressure, for closing it. The effect of this force is obvious in top-hinged gates, which remain closed under the influence of their own weight except during each of the two daily ebb tides if there is sufficient water pressure to open them. Differences in water pressure are created by the hydraulic head differential (that is, uneven water levels on both sides of the gate) and are caused by (1) tidal cycles and magnitude of tides, (2) inflow into the inlet pool (also called reservoir or backwater pool) that forms immediately upstream of the flood box, and (3) the extent to which this inlet pool was drained during the previous gate-opening period. As water level in the downstream side of the gate rises during flood tide, its pressure will exceed that of water on the upstream side and the gate will close (see tide gate operation cycle in figure 4) (Charland 1998, 2001).

The force of gravity is a constant; hence, the restorative force for each tide gate is determined by its weight, its buoyancy in water, and the force of friction at the hinges. Lighter and smaller gates open more readily (under a smaller hydraulic head differential) than heavier and larger gates (USACE 2001). The restorative force of a gate is lessened if the lid is made of a buoyant material such as wood. However, wood can become waterlogged and weigh progressively more. If this happens, the restorative force

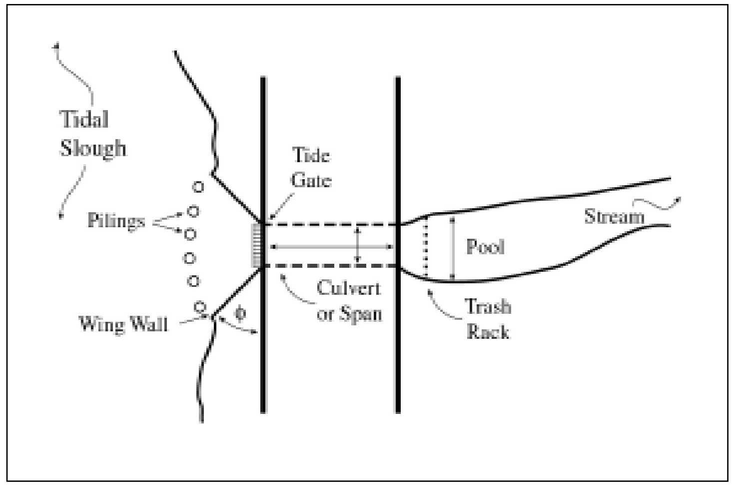


Figure 1. Schematic view of flood box with tide-gated culvert. Tide gate is attached to downstream end of culvert. Supplementary structures are pilings, trash rack, and wing walls.

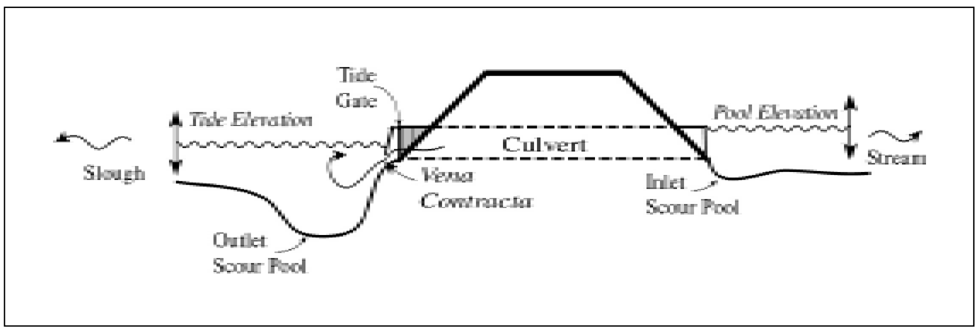


Figure 2. Lateral schematic view of a flood box with a top-hinged tide gate attached to downstream end of culvert.

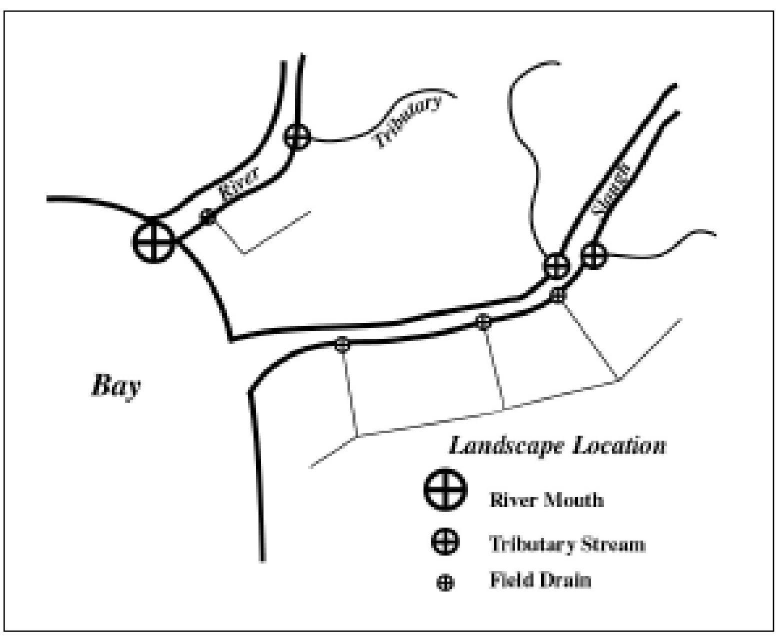
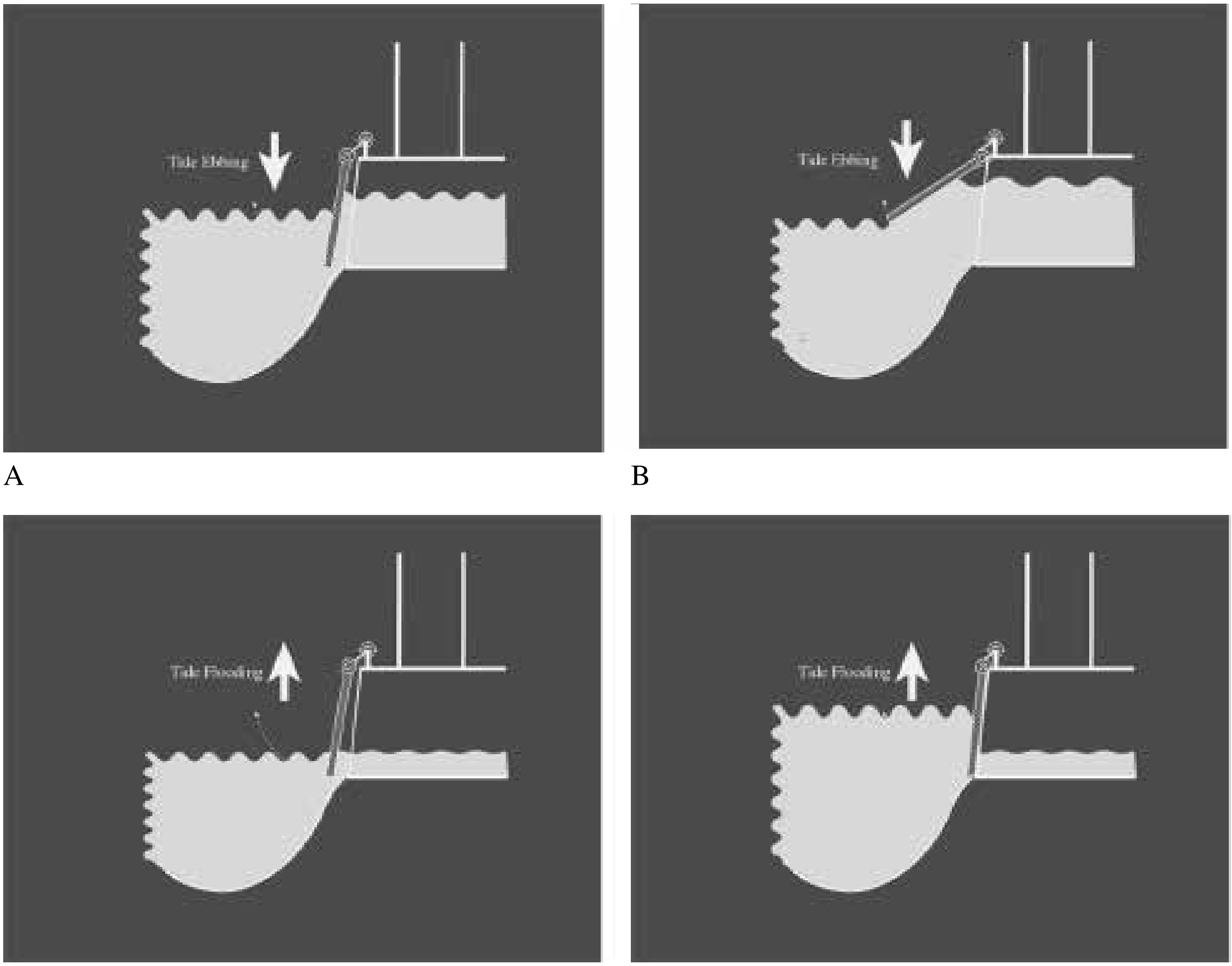


Figure 3. Common tide gate locations at the mouth of rivers, small tributary streams, tidal nonriverine channels, and field drainage ditches.



A B C D

Figure 4. Tide gate operation cycle. A. Tide gate begins to open when water pressure in culvert overcomes pressure of water on downstream side during ebb tide. B. Tide gate is wide open during ebb tide. C. Tide gate begins to shut when upstream water level drops and tide begins to rise. D. Tide gate is shut during flood tide.

of the gate will increase over time, and the gate will fail to operate as intended. Improperly designed or installed hinges, corroded hinges, or hinges that are damaged by waterborne debris can contribute to a large restorative force through friction. The force of friction can increase the restorative force of a gate to the extent that normal downstream flows will not produce sufficient hydraulic head differential to overcome it and the gate will remain closed. Therefore, proper sizing, installation, and periodic maintenance are necessary to ensure that a tide gate works as intended. Considering this and the fact that they can be easily jammed by floating pieces of wood, tide gates need to be examined regularly during both flood and ebb tides to verify that they are operating properly.

Importance of the Invert Elevation

There is a crucial interrelationship among stream flows, tide gate invert (that is, bottom sill) elevation, and a wide range of environmental parameters. Upstream hydrology, in combination with tidal cycles, is the driving force in the opening-draining-closing cycle of tide gates. This cycle directly controls fish passage and water chemistry and indirectly influences a variety of biological factors.

Monitoring of the new Larson Slough tide gate in Larson Slough, Coos Bay, Oregon, revealed that at low summer stream flows the gate did not open at all during some of the tide cycles. This happened because the inlet pool, upstream from the flood box, drained completely during a low tide, and the reduced upland flow was insufficient to fill in the pool and raise the water level above that of the subsequent low tide. These conditions seem to occur during significant periods of time when the difference between the lower and higher of the low tides is large. Figure 5 illustrates the cyclical pool and tide elevation variation over a two-week period during the fall of 2003 at the Larson tide gate.

During the tidal cycle when sequential low tides were relatively similar (shown in figure 5 by the valleys on the broad gray line between September 26 and September 28), the tide gates opened twice a day (which means that they opened every tidal cycle even with low stream inflows). In contrast, because the difference in elevation between the two daily low tides increased over the following two weeks and the upland flows (combined with leakage through the dike) were not sufficient to fill the inlet pool, a positive hydraulic head differential between the inside and outside of the gate could not be created to force the gate open. This is the result of having the invert elevation (bottom sill) of the tide gate below the level of the lowest of low tides (September 30, 2003, in this series). At a higher invert elevation, such as -4 ft NGVD (National Geodetic Vertical Datum) on figure 5, freshwater flow into the inlet pool would provide sufficient head difference to open the gates during both daily low tides.

Varying the invert elevations has many other environmental effects. In terms of fish passage, while the higher invert elevation discussed above would result in the tide gates opening twice daily, it would also result in water spilling over the sill during periods when low tides are below the invert elevation. For example, with an invert elevation of -4 ft NGVD, there could be as much as a 5 ft drop between the sill and the tidal water surface elevation, thus raising fish passage issues similar to those with perched culverts (see "Culverts") (Robison et al. 1999).

Beyond concerns over fish passage, the invert elevation at the Larson Slough tide gate was established with the objective of improving the connectivity of the system and sediment transport from upstream, through the flood box, and into the slough. Pre-project channel bathymetry data were recorded to create a two-dimensional longitudinal profile from approximately 300 yards (274 m) upstream of the structure to 200 yards (180 m) downstream into the estuary. This stream longitudinal profile was used to determine the original natural gradient of the reach and to establish the invert elevation of the new tide gate's culvert along that gradient. This ensured the replication, to some degree, of the original conditions in the tidal channel before the placement of the first Larson Slough tide gate in 1927. The expectation is that the sill elevation of the new tide gate will facilitate the natural flushing of sediments through tidal filling and draining.

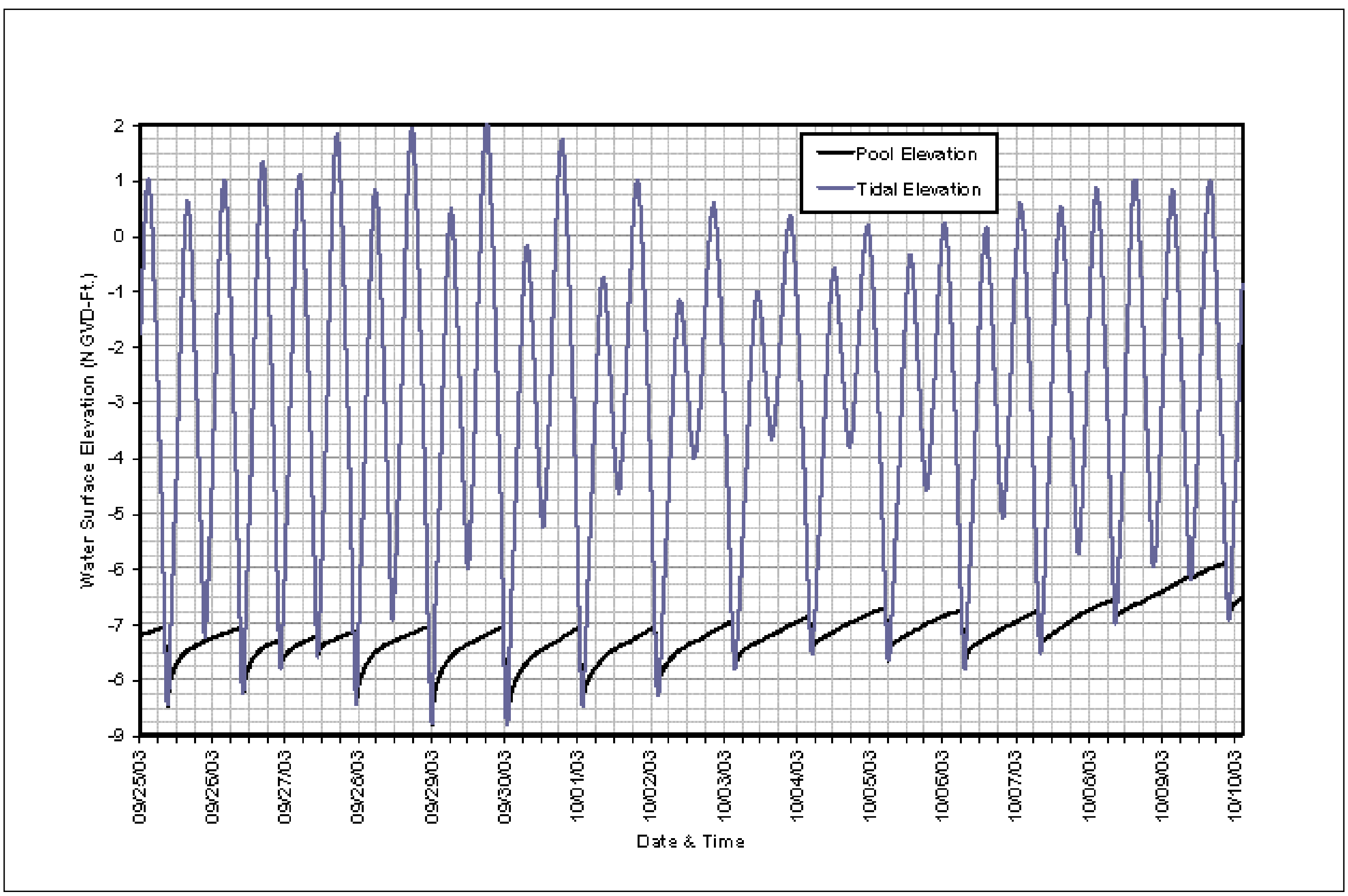


Figure 5. Larson tide gate water surface elevations (September 25–October 10, 2003).

The replacement of the old top-hinged tide gates of Larson Slough with new side-hinged gates that are set at a lower invert elevation and do not leak has allowed the complete draining of the inlet pool with every tide cycle, something that did not occur before, and has led to a change in the salinity regime above the dike. Before the old gates were replaced, a wedge, or "tongue," of salt water formed in the bottom of the inlet pool. This salinity was the result of a comparatively high backflow of brackish water into this pool during high tides, which resulted from the combination of leakage around the gate (that is, failure to seal) and seepage underneath the concrete apron of the culvert. With the exception of the summer, the saltwater wedge was reduced or eliminated by the downstream flow and water mixing that occurred every time the gates opened. Summer flows were insufficient to mix the upper layer of freshwater with the denser salt water in the bottom of the pool, and the saltwater wedge persisted through the opening-draining-closing cycles of the gates during this season. Saline water wedges underneath freshwater layers were also observed in other pools farther upstream and in deeper channels during the summer. With higher freshwater inflows beginning with fall rains, most of these salt pools and wedges would be washed out in a tide gate cycle. Although a salinity wedge forms in the pool behind the new Larson Slough gate as a result of leaks around the door seals, its volume is considerably smaller than with the old gate because of more complete draining.

The change in pool volume (and wetted perimeter) and salinity regime brought about by the gate replacement in Larson Slough also altered the biomass and the species composition of aquatic vegetation upstream of the dike. The pre-project salinity regime created conditions in the upstream inlet pool suitable for the establishment of marine aquatic vegetation similar to that found in the estuary. Three marine plants were found in the pool during baseline monitoring. Both species of eelgrass (Zostera marina and Z. japonica) were found, as well as specimens of the genus Ulva (a fine filamentous green algae). As it is in the estuarine environment, Z. marina was found in deeper, more saline water, whereas Z. japonica was found more frequently along the margins and in the upstream end of the pool. Ulva were found even higher along the margins where desiccation was a daily occurrence. As a result of changes in the salinity regime, two years after the replacement of the tide gate Z. marina is completely absent and Z. japonica has only remnant populations showing little growth and vigor. In addition, the large biomass of the green alga Enteromorpha intestinalis, found when a larger pool existed, has been reduced to about 10% of its pre-project extent and volume. This change in the abundance and type of aquatic plants affects nutrient uptake, fish habitat quality, and possibly water temperatures and bacterial abundance.

Environmental Effects of Dikes and Tide Gates

Effects on Upland Flooding and Water Flow

Dikes and tide gates are installed to prevent the upland flow of water under the influence of rising tides. This, in turn, disrupts the movement of the "front" of the estuary, thus altering the saltwater wedge and the associated water circulation pattern. By allowing water to flow in only a single direction, tide gates alter the pulsed nature of upstream habitats; control upland flooding; change the velocity, turbulence, and pattern of freshwater discharge; block the mixing of waters of different temperatures; and increase upstream sedimentation (Odum 1970; Portnoy 1991; Khaleel and Othman 1997; Bates 1999; Middleton 1999).

Effects on Channel Characteristics

The geometry (or cross-sectional shape) of channels is altered by tide gates in two ways. First, upstream scour tends to form an inlet pool above the flood box, and the water jet (that is, vena contracta) through the culvert forms a deep scour pool on the outlet end (see figure 2). Second, if the flood box is replaced and the invert elevation of the new culvert is set lower than the first one, upstream erosion of the accumulated sediments could result in changes to the channel morphology.

The lack of a two-way flushing cycle causes sediments to fill upland channels instead of reaching the estuary below (Vranken et al. 1990; Anisfeld and Benoit 1997; Portnoy and Giblin 1997b; Anisfeld et al. 1999; Bates 1999). The increased sedimentation can occur even in upstream segments that are considered to be above tidal influence. For example, when the tide gate on Joe Leary Slough, a coastal stream that drains into North Puget Sound, Washington, was closed, the amount of suspended sediment in waters above tidal influence decreased by 75% (Bulthuis 1996). When sediments and detritus fill in upland channels, they do not reach the estuary and thus render it less productive (Roman et al. 1984). Such a drop in estuarine productivity was documented, for example, in the Bay of Fundy, New Brunswick, Canada, after 20 major tide gates and other tidal barriers on tributary rivers were installed (Harvey et al. 1998).

Effects on Water Temperature

By blocking the normal bidirectional movement of water, tide gates also disrupt the normal, gradual change in water temperature that occurs when waters of different temperatures mix and circulate. Consequently, tide gates create sharp transitions in water temperature (Bates 1999; Portnoy 1999; Portnoy and Giblin 1997a; Portnoy et al. 1987a). For example, in Blind Slough, Tillamook Bay, Oregon, a tide gate caused a 2˚C–5˚C difference in water temperature above and below the tide gate. When connectivity was restored following the installation of a new tide gate, the temperature difference dropped to 1˚C within five hours (D. Reynolds, Tillamook County Performance Partnership, personal communication). Such abrupt changes in water temperature may represent a barrier to migrating fish, which tend to favor gradually changing temperature gradients (Jonsson 1991; Bakshtansky et al. 1993; Berggren and Filardo 1993; Kynard 1993; Russel et al. 1998; Bates et al. 1999).

Because tide gates cause freshwater stagnation and restrict tidal inflow, they tend to increase upstream water temperatures. In this manner, tide gates can potentially create unsuitable conditions for juvenile salmon that use the lower river and the upper estuary as nursery grounds. Under the Clean Water Act, the temperature criterion established for noncore rearing habitat for salmon and trout is 64.4˚F (18˚C) (Oregon Department of Environmental Quality 2004).

Effects on Water and Soil Salinity, Ph, and Heavy Metals

Tide gates prevent salt water from moving upstream, thus reducing the salinity of upstream habitats. Water salinity in estuaries varies daily and seasonally. Daily variations are influenced by tides, as water with higher salinity flows from the mouth of the estuary inland during flood tide and back toward the ocean during ebb tide. Seasonal variations in tidal inundation depend largely on rain- or snowmelt-induced changes in the discharge of rivers and streams. The upstream limit of brackish water is determined by the tidal range (that is, the difference between high and low tides for any specific cycle) and by the amount of freshwater inflow entering the estuary from tributary streams (Coats et al. 1989; Odum et al. 1995).

When closed, tide gates prevent the flooding of upland channels by brackish water. As a result, major differences in salinity develop between both sides of tide gates. For example, Scalisi (2001) examined water salinity below and above the tide gate in Larson Slough and found that it reached 18–19 ppt (parts per thousand) below the tide gate but less than 2 ppt above it.

The exclusion of salt water can lead to oxygen depletion in the water when the organic matter, which is normally kept under anaerobic (without oxygen) conditions in the soil, begins to oxidize. Furthermore, the oxidation of peat (accumulated dead plant material that is normally stored under anaerobic conditions) can cause the surface of the marsh to subside and compact (Roman et al. 1984), in some cases by as much as 37 in (0.9 m) (Portnoy and Giblin 1997b). Soils in estuarine marshes are naturally anaerobic. When the operation of tide gates begins to lower the salinity of soils on the upland side of dikes and expose them to periodic desiccation, these soils become exposed to air, and a variety of aerobic (oxygen-driven) processes begin in them (Richardson and Vepraskas 2001). If this occurs, immobilized, reduced sulfides bound to the soil iron (as iron pyrite) are oxidized and converted into sulfates and sulfuric acid. These compounds make the soil acid (lower its pH) (Anisfeld and Benoit 1997; Portnoy and Giblin 1997b), and this acidification can in turn cause metals in the soil (that is, iron, lead, aluminum, copper, silver, and cadmium) to be released into the water (Anisfeld and Benoit 1997). The mobilization of metals such as iron and aluminum will kill many marsh plants.

When the gate opens, pooled freshwater moves into the estuarine channel, creating a tongue of fresher water that, through turbulence, mixes as it moves down the estuary. The speed of the salinity mixing, and the extent of the freshwater tongue, is related to the type and size of gate, the amount of freshwater pooled upstream, and the relative difference in salinity between fresh and brackish water in the area (Jay and Kukulka 2003).

Over time, all tide gates begin to leak. Leaks occur if the seal between the gate and the supporting structure is uneven, if debris is caught when the gate closes, or if culverts corrode or crack upstream from the gate. In addition, leaks appear when salt water "percolates" through a dike's fill material because of the hydraulic pressure caused by high tides. Whenever brackish water enters the upland side of a dike, it occupies the bottom layer of water in upstream pools. When the tide gate opens, if mixing does not occur, the less dense freshwater flows into the estuary, leaving residual pools of brackish water upstream.

Effects on Plant Communities

The consequences of the upstream reduction in salinity caused by tide gate operation are changes in the plant community, with salt-tolerant plants being gradually replaced by freshwater plants, many of which can be used as forage for domestic animals. In many instances, such changes in vegetation composition have been one of the reasons for putting dikes and tide gates in estuarine marshes in the first place. The changes introduced by tide gates can be quite severe. For example, a freshwater system developed in the Herring River Salt Marsh, Cape Cod, Massachusetts, following the placement of dikes and tide gates in 1908 to exclude tidal water. Nine decades later, trees are growing in what had been a salt marsh. The abundance of animals was greatly reduced; fewer species of invertebrates and fish were found in the freshwater habitats, compared to what was found in the brackish water marsh below the tide gate (Roman et al. 1984; Roman et al. 1995).

Effects on Fish, Fish Habitats, and Fish Passage

Only recently have the effects of dikes and tide gates on salmon and trout movement and habitat quality attracted the interest of agencies and watershed councils. In the particular case of salmon and sea-run trout, tide gates may negatively affect them not only by preventing their migration but also by deteriorating the quality and connectivity of their habitats.

In addition to the indirect negative effects that tide gates can have on fish by altering the composition of the plant and invertebrate community in their estuarine habitats, tide gates can affect migrating fish in a more direct manner. The abrupt change in salinity caused by a tide gate can affect migrating fish in different ways.

For example, juvenile salmon need a gradual change in salinity as they undergo the physiological changes needed to transition from freshwater to salt water. If they are suddenly transferred from one environment to the other, they can die from osmotic shock. Because of this, juvenile salmon actively seek waters where salinity gradually changes during their period of residence (which ranges from days to months, depending on the species) in estuaries. This is crucial to their survival (Otto 1971; Groot and Margolis 1991).

Abrupt changes in salinity can also affect adult salmon migration. Russell et al. (1998) found that Atlantic salmon were disoriented by the abrupt change in salinity when they migrated upstream past a dike. On average, it took these salmon 2.5 days to recover from the abrupt change in salinity before they were able to continue their migration, although some remained in the same area for over nine weeks before they resumed their upstream journey. It is possible that this delay increases predation risk (J. Souder, personal observation).

When the drop in salinity and water level allow the organic matter that is kept in marsh soils under anaerobic conditions to oxidize, the resulting fall in dissolved oxygen levels can cause massive fish killings. An incident of this type was observed when oxygen levels in the Herring River Estuary, Cape Cod, Massachusetts, remained very low for up to three weeks and killed thousands of migrating herring (Portnoy et al. 1987b; Portnoy 1991).

Estuaries play a critical role in juvenile salmonid survival during the transition from freshwater to salt water (Pearcy 1992). Estuarine habitats provide juvenile salmon with (1) a productive feeding area, (2) a refuge from marine predators, and (3) a transition zone for gradual acclimation to salt water (Thorpe 1994).

Because tide gates interfere with water flow in the boundary zone between estuaries and streams, they alter the coastal marsh habitats of juvenile salmon (Beamer and LaRock 1998). They do this by changing not only water quality and channel characteristics, but also the species of aquatic plants and invertebrates (for example, insects and crustaceans) juvenile fish rely on for cover and food.

Traditional tide gates are designed to reduce or prevent the upstream flow of tidal water and to reduce fluctuations of water levels upstream. The reduction in upstream tidal range is often carried out for flood control, but floodplain environments are critical for anadromous salmonids. Juvenile salmon often spend a large portion of their freshwater residence in floodplains and their associated channels. It has been observed that the growth and survival of juvenile salmon that were able to utilize these floodplain habitats were greater than those of fish that were confined to main-stem channels (NRC 1996). The reduction in amount and quality of estuarine habitat can have a substantial effect on the survival of juvenile salmon and trout during the critical transition period from fresh to marine environments.

Two factors influence the extent to which a tide gate represents a physical barrier for fish passage. One is the length of time the gate is closed and the other, how wide the gate opens. Any tide gate represents a total barrier to fish passage during the period of time it remains completely closed. The length of this period depends on the magnitude of the tidal exchange (the difference between high and low tides), the water inflow into the upstream inlet pool between opening cycles, and the degree to which this pool emptied during the previous cycle. Under normal conditions, top-hinged tide gates will not open until the water level inside the culvert is higher than the water level on the downstream side. These gates will close only when the water level on the estuary side is equal to or higher than the water level inside. Because tidal cycles are approximately 12 hours long, and tides flow in about half of that time and flow out the other half, top-hinged tide gates are expected to remain closed at least 50% of the time (that is, 6 hours within each cycle, assuming the upstream pool empties completely during each cycle and the gate closes by the combined effects of its own weight and slack tide). However, depending on how they are installed and the characteristics of the area they drain, gates may remain closed for longer periods. For example, Scalisi (2001) reported that during February 2001 the tide gate in Larson Slough, Coos Estuary, Oregon, opened 4 hours after the beginning of ebb tides and closed at slack tide, thus representing a total barrier to fish passage 75% of the time.

Tide gates not only create direct physical barriers to fish passage but also originate indirect obstacles to fish in the form of elevated water velocities and turbulence. Velocity criteria established for fish passage in culverts are similar to those used for tide gates. In Oregon, the water velocities recommended by the Department of Fish and Wildlife are 5 ft/sec for adult salmonids in culverts 60 to 100 ft long, and 2 ft/sec for juvenile salmonids (Robison et al. 1999). Average water velocities through tide gates are a function of the upstream-downstream hydraulic head differential and the width of the opening. Opening width varies through the tidal cycle and is influenced by the resistance of the gate to opening, which depends on its weight and design. Water velocities through side-hinged gates are lower than through top-hinged gates of similar size and weight because less force is required to keep side-hinged gates open. Also, lighter aluminum gates require less force to open, and as a result, velocities through their openings are lower than with steel or cast iron gates of a comparable size.

Water turbulence results from the effects of shear forces caused by drag in water velocity at the edges of channels, through obstructions, or where differences in viscosity occur (Goldstein 1965). Cross-sectional area, substrate and bank roughness, and protuberances in the channel all reduce the velocity of the layer of water that is in contact with the walls of the channel (or culvert, in the case of a flood box) compared to the higher velocity of the rest of the water column (Goldstein 1965). When a critical threshold in the velocity difference between these layers of water is reached, turbulent flow results. Turbulence and the associated bubbling of air in water cause vibration and noise that, depending on their magnitude, may present obstacles to fish movement. Heavy top-hinged tide gates produce a high-velocity jet of water, called vena contracta (see figure 2), that creates turbulence and bubbling (Pethick and Harrison 1981). This water jet is caused by the combined effects of the upstream-downstream water level differences, the tendency of the gate to close by the effect of its own weight (or restorative force), and the size of the gate. On the basis of observations at the tide gates in Larson and Coalbank Sloughs, Oregon, turbulence is lower with side-hinged gates than with top-hinged ones (Coos Watershed Association, unpublished data). Because the forces that tend to keep the gate closed are lower in both side-hinged and lightweight tide gates, the jet of water and its resulting water turbulence and bubbling are practically eliminated.

Culverts

Fish passage problems at tide gates are a combination of two separate processes: passage through a culvert and passage past the tide gate that is attached to the culvert. The problem of fish passage through culverts is well studied, and specific guidelines have been established to make culverts fish friendly. In contrast, the problem of fish passage through tide gates is poorly understood, and little information exists about specific remedies needed to make tide gates fish friendly.

The design, size, and installation of culverts to allow fish passage have been well studied, and there are several manuals that discuss what makes a culvert fish friendly (Ebel 1977; Adams et al. 1986; Powers 1997, 1998; Moore et al. 1998; Poulin and Argent 1998; Bates et al. 1999; Robison et al. 1999; Porior 2000). Moore et al. (1999) compiled an annotated bibliography of 96 publications about fish passage through culverts (available at www.stream.fs.fed.us/fishxing/biblio.doc).

Additionally, the U.S. Forest Service's San Dimas Technology and Development Center in California developed software called Fishxing that will evaluate an existing or proposed culvert for fish passage. This software considers many variables, including the species of fish under consideration, culvert characteristics (such as shape, length, size, and roughness), and high- and low-level water flow. A free CD with this software can be obtained by writing to Publications, USDA Forest Service, San Dimas Technology and Development Center, 444 E. Bonita Ave., San Dimas, California 91773. It can also be downloaded from www.stream.fs.fed.us/fishxing.

Changes in water velocity, turbidity, and light associated with culverts elicit avoidance behavior in fish at culvert entrances (Robison et al. 1999). The following are some of the most important parameters that must be considered when designing culverts for fish passage: water velocity, water depth inside the culvert, water turbulence, drop at outlet, resting pools, and debris accumulation at culvert inlet (Bates et al. 1999; Robison et al. 1999).

Water velocity is a major problem for fish passage. If the diameter of a culvert is greater than or equal to the width of the stream channel, water velocity will not increase through a culvert. However, when the culvert diameter is less than the channel width, the culvert will cause water velocity to increase (Robison et al. 1999). Water velocity can be a barrier to fish passage if it exceeds the swimming ability of the fish. "Swimming ability" is determined by a number of factors, among which are species, size, condition and age of the fish, and length of culvert. When designing culverts, it is important to consider the sustained, cruising (prolonged), and darting (burst) speeds of the species that are expected to pass (Powers 1997). The sustained speed is the speed that a species can maintain for a relatively long period (minutes to hours). Cruising and darting speeds are faster and are used to escape predators, to accelerate past an obstacle, or to move through an area of high turbulence or velocity. Cruising speed can be maintained for a few minutes, whereas darting speed can be maintained for only a few seconds. A fish usually has to rest after swimming at cruising or darting speeds. These speeds have been used to establish maximum water velocities to enable salmon passage through culverts of varying lengths.

Table 1 shows the maximum water velocities required in Washington State to ensure upstream passage of adult salmon and steelhead through culverts. (“Maximum” refers to the volume of water allowable during a two-year, seven-day flood.) In addition, both minimum flow depth through the culvert and maximum hydraulic drop should be 0.8 ft (24 cm) for pink and chum salmon, and 1.0 ft (30.5 cm) for chinook, coho, and sockeye salmon, and for steelhead.

Table 2 shows the average water velocities required at high flow in Oregon for upstream salmon and steelhead passage through culverts (Robison et al. 1999). In Oregon, if the culvert length is greater than 100 ft (30.48 m), artificial streambeds must be created in the culvert to enable juveniles to seek desired flow rates and to provide many resting areas.

Table 3 shows the maximum water velocities allowed through culverts in British Columbia to ensure fish passage (Poulin and Argent 1998). In British Columbia, when a culvert is longer than 98.43 ft (30 m), streambed simulation must be incorporated into the culvert to enable passage of juveniles.

Although the recommended maximum water velocities in Washington, Oregon, and British Columbia are relatively similar, they are not exactly the same. This may be due to differences caused by using different fish stocks and different testing conditions and methods.

If water velocities exceed the recommended speeds, salmon and trout will be unable to pass upstream through the culvert because they will become exhausted before reaching the culvert inlet (upstream opening). Hinch and Bratty (2000) found that successful migrants were those that never needed to exceed three minutes of continual swimming at cruising (prolonged) speed. When water velocity in a culvert exceeds the recommended maximum, one solution that has been used in different cases is the creation of resting areas within the pipe. Such low-velocity shelters are created by baffles, weirs, or large rocks placed inside the culvert and are theoretically used by fish to rest momentarily before resuming the upstream migration through a culvert (Storzer and Simpson, no date).

Recommended maximum water velocities for juvenile salmonids are much lower than for adults because swimming ability for a species is directly related to the age and size of the individuals being tested (Powers 1997; Robison

Table 1. Maximum water velocities required in Washington State to ensure upstream passage of adult salmon and steelhead.

Culvert Length	Pink and Chum Salmon	Chinook, Coho, and Sockeye Salmon and Steelhead
10–60 ft (3–18.3 m)	5 ft/sec (1.52 m/sec)	6 ft/sec (1.83 m/sec)
60–100 ft (18.3–30.5 m)	4 ft/sec (1.22 m/sec)	5 ft/sec (1.52 m/sec)
100–200ft (30.5–61 m)	3 ft/sec (0.92 m/sec)	4 ft/sec (1.22 m/sec)
>200 ft (61 m)	2 ft/sec (0.61 m/sec)	3 ft/sec (0.92 m/sec)

Table 2. Average water velocities required at high flow in Oregon to ensure upstream passage of salmon and steelhead.

Culvert Length	Adult Salmon and Steelhead	Juvenile Salmon and Steelhead
<60 ft (<18.3 m)	6 ft/sec (1.83 m/sec)	2 ft/sec (0.61 m/sec)
60–100 ft (18.3–30.5 m)	5 ft/sec (1.52 m/sec)	2 ft/sec (0.61 m/sec)
100–200 ft (30.5–61 m)	4 ft/sec (1.22 m/sec)	---
200–300 ft (61–91.5 m)	3 ft/sec (0.92 m/sec)	---
>300 ft (>91.5 m)	2 ft/sec (0.61 m/sec)	---

Table 3. Maximum water velocities through culverts in British Columbia to ensure fish passage (Poulin and Argent 1998).

Culvert Length	Adult Coho and Chinook Salmon, and Steelhead	Adult Pink and Chum Salmon	Juveniles (all species)
<58.5 ft (<18 m)	5.8 ft/sec (1.8 m/sec)	4.9 ft/sec (1.5 m/sec)	2 ft/sec (0.6 m/sec)
58.5–97.5 ft (18-30 m)	4.9 ft/sec (1.5 m/sec)	3.9 ft/sec (1.2 m/sec)	2 ft/sec (06 m/sec)
97.5–195 ft (30-60 m)	3.9 ft/sec (1.2 m/sec)	2.9 ft/sec (0.9 m/sec)	---

et al. 1999). Smaller and younger fish cannot swim as fast or for as long. For example, maximum sustained swimming speed for coho salmon is only 1.0 ft/sec (0.30 m/sec) for subyearlings, and 1.3 ft/sec (0.40 m/sec) for yearlings. Their prolonged swimming speed is 1.1–1.2 ft/sec (0.34–0.37 m/sec), and darting speed is 2.1–2.4 ft/sec (0.64–0.73 m/sec) (Powers 1997). Bates (1999) recommended a maximum water velocity of 1.3 ft/sec (0.4 m/sec) to enable juveniles longer than 2.5 in (60 mm) in fork length to migrate upstream, and that the maximum be only 1.1 ft/sec (0.43 m/sec) for fry less than 2.5 in (60 mm) in fork length. Robison et al. (1999) recommended the maximum water velocity for upstream migration of juvenile salmonids of all species to be 2 ft/sec (0.61 m/sec).

Ways to increase passage of young fish include using corrugated culverts, which increase roughness and create zones of low velocity along the edge; placing weirs or baffles in the culvert; constructing natural channels in the culvert; and keeping the slope of the culvert to near zero. These approaches reduce velocity or create areas in the culvert where velocity is lower and fish can choose the most favorable among different water velocities (Bates et al. 1999).

Powers (1997) found that culvert slope, roughness (amount of corrugation vs. smooth pipe), and water velocity determined the ability of coho salmon fingerlings to migrate upstream through a culvert. A slope of just 0.15% in a smooth culvert reduced fish passage to 20%. If a corrugated culvert was used, the slope needed to reduce passage to 20% ranged from 0.71% to 1.44%, depending on the degree of corrugation. In a culvert with highly corrugated sides, 80% passage was achieved with a water velocity that averaged 1.2 ft/sec (0.37 m/sec) and had a maximum water velocity of 1.3 ft/sec (0.40 m/sec). When water velocity increased to 2.8 ft/sec (0.85 m/sec) with a maximum of 3.4 ft/sec (1.04 m/sec), passage decreased to 20%. Juveniles were observed to seek low-velocity boundary-layer water along culvert sides when water velocity reached 0.4 ft/sec (0.12 m/sec).

Although many would assume that juvenile salmonids migrate only in a downstream manner, the fact is that the young fish migrate upstream on many occasions in search of suitable rearing habitats. Water velocity in many culverts is often too great to allow upstream passage of juvenile fish, except during periods of low flow. This can have drastic effects on the survival of the fish (NRC 1996).

For culverts in tidally influenced waters, the recommended flow requirements for culverts should be met for at least six daylight hours each day on 90% of the days during salmon migration (Bates et al. 1999).

Bakshtansky et al. (1993) and Haro et al. (1998) found that velocity at culvert and bypass entrances is crucial for downstream migration of juvenile salmonids. Atlantic salmon smolts avoided bypasses if there was a sudden change in velocity and they were reluctant to enter dark structures (Haro et al. 1998). Salmon smolts like to migrate downstream in schools (Bakshtansky et al. 1993; Haro et al. 1998), and structures that do not allow for this may affect their migration. Haro et al. (1998) found that when water velocity was greater than 6.6 ft/sec (2 m/sec), schools of Atlantic salmon smolts were dispersed because the fish that entered the faster water were swept downstream while the others remained above the culvert. Apparently, both the size of the opening and the rate at which water velocity changes are important.

The depth of the water column inside a culvert also affects the ability of salmon to migrate through it. A minimum depth is needed because partially submerged fish cannot swim or breathe efficiently; additionally, if water is too shallow, fish can scrape the bottom of the culvert and injure themselves (Robison et al. 1999). Bates et al. (1999) report that adult chinook salmon, coho salmon, sockeye salmon, and steelhead require a minimum water depth of 12 in (30.5 cm), whereas adult pink salmon and chum salmon require a minimum water depth of 10 in (24.5 cm). Robison et al. (1999) list minimum water depths of 12 in (30.5 cm) for adult steelhead and chinook salmon, 10 in (24.5 cm) for all other adult salmon, and 8 in (20 cm) for juveniles.

A third potential culvert-related impediment to fish migration is the hydraulic drop (that is, the distance between the lower lip of the culvert outlet and the surface of the pool below). If the culvert is improperly installed, with the outlet perched above the stream water level, fish are forced to jump into or out of the culvert. Bates et al. (1999) recommend that the hydraulic drop not exceed 12 in (30.5 cm) for adult chinook salmon, coho salmon, sockeye salmon, and steelhead and 10 in (24.5 cm) for adult pink salmon and chum salmon. Although salmon are known for their jumping ability, they are not well adapted to leap several feet into a pipe opening. If a jump is required, a resting pool below the culvert outlet with a depth 125% the height of the jump is required to enable the fish to jump that height (Robison et al. 1999).

Types of Tide Gates

Because all tide gates block fish passage during all or most incoming tides, there is no such thing as a "fish-friendly" tide gate, only "fish-friendlier" ones. The many different types of tide gates that exist can be grouped into two major categories: traditional designs and new designs.

Traditional Designs

Traditional tide gates are all top hinged or top chained and have either a round or a square or rectangular lid that is suspended from the upper edge of a culvert or a beam. Round lids are usually made of metal, whereas square or rectangular lids are made of either wood or metal. In the Pacific Northwest, most tide gates currently in use are one of these two types.

Top-Hinged, Round, and Cast Iron

Traditional manufactured tide gates have a top-hinged, round lid made of cast iron, although some new ones are made of steel (Charland 1998, 2001; Thomson and Associates 1999, 2000) (figure 6). These gates are usually heavy; for example, a round cast iron tide gate 4 ft in diameter (1.22 m) weighs 750 lb (340 kg) (B. Murphy, at Waterman, California, personal communication). As a result, the restorative force of a top-hinged cast iron tide gate tends to be large, and the gate does not open very wide unless the hydraulic head differential is large. When the hydraulic head differential decreases, the gate closes quickly. This means that top-hinged cast iron tide gates are usually open only during brief periods of ebb tide.

A top-hinged cast iron tide gate is attached to a cylindrical culvert of corrugated metal by means of a single- or double-hinged system. A double-hinged attachment provides flexibility in the hinging system when debris is jammed between the tide gate and the culvert. Without the double-hinged system, trapped debris could bend or break the hinges or the gate. If the hinges are damaged, the tide gate will not swing freely, and this could either keep the tide gate open all the time or increase the restorative force to the point where the gate does not open.

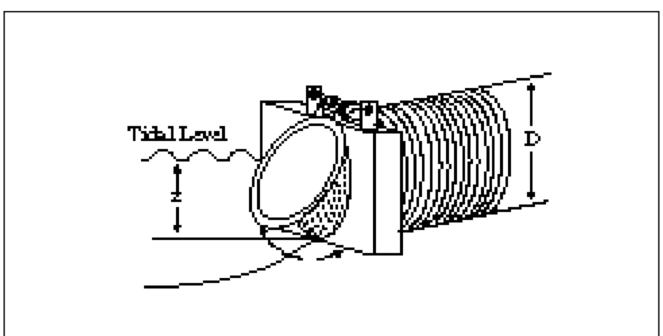


Figure 6. Top-hinged, round, cast iron tide gate, attached to cylindrical culvert.

This design is very efficient in draining upstream lands and in preventing back flooding during high tides if sized properly. Therefore, it has been the one of choice to convert wetlands into agricultural lands and to prevent tidal flooding. Other advantages of this type of tide gate are that (1) it is simple to construct and install, (2) it requires little maintenance, and (3) it has a long life span. A cast iron tide gate can be affected by electrolysis, but many normally functioning tide gates are decades old, which indicates that this is not a major problem. Cast iron tide gates can be damaged by floating debris, but these gates are stronger than most other types and physical impairment is less of a concern with them. But their weight also tends to break the end of a culvert if scour has washed away the dike filling that supported the culvert.

Because this type of tide gate is very efficient mechanically, virtually no water moves upstream during flood tide. Consequently, the system's connectivity is disrupted and the quality of the water on the upland side of the dike is markedly altered, particularly if the lower reach of a stream above a dike used to be regularly inundated by tidal brackish water before the gate was installed.

Furthermore, this type of tide gate hinders or prevents fish passage in a number of ways (Charland 1998; Thomson and Associates 1999, 2000). First, the tide gate is open for only two brief periods each day (and sometimes only one, depending on seasonal changes in upland flow and tide levels), which means there is little opportunity for fish to migrate past such a barrier. Second, if the tide gate doesn't open wide enough, some fish may be deterred from passing because of the size of the opening. Bates (1999) found that a round cast iron tide gate 4 ft (1.22 m) in diameter was a barrier to fish passage because the restorative force was so great that none of the passage conditions needed by fish were met. Finally, fish passage is strongly influenced by water velocity, and the velocity of water as it passes through the tide gate is greatly influenced by the size of the opening. The huge restorative force generated by this type of tide gate usually means the opening will be narrow, and the resulting jet of water that escapes downstream past the tide gate will create turbulence and bubbles, which will preclude fish passage during the only periods when it would be possible.

Top-Hinged, Rectangular, and Wood

The other type of top-hinged tide gate has a rectangular or square lid and is made of wood. It is installed on culverts that are either round and made of corrugated metal or square and made of concrete (Charland 1998, 2001; Thomson and Associates 1999, 2000). Often, wooden tide gates have metal bands to reinforce the wood. As is the case for the round metal gates, the lids of these gates can be attached to culverts by hinges or hung from a top beam by chains. These tide gates are usually rectangular and can be quite large—10 x 12 ft (3.05 x 3.66 m) gates are not uncommon. Their large size, combined with the tendency of the wood to become waterlogged over time, makes these lids increasingly heavy and less buoyant.

The advantages and disadvantages of this type of tide gate are similar to those described for top-hinged cast iron gates. Although the wooden lids are not affected by electrolysis the way the iron ones are, the bolts that hold the wood together can become weakened over time. Nonetheless, their life span is also of several decades. One advantage this type of tide gate has over the cast iron version is that it can be manufactured locally and is often less expensive.

New Designs

Restrictions on water exchange and fish migration by the traditional type of top-hinged tide gates have prompted the design of new models of tide gates that are promoted as environmentally and fish friendlier. Several new designs have been proposed; some of them seem to have remained at the conceptual stage, while others are currently in use.

Compared to the most restrictive gates, a "fish-friendlier" installation should have a gate that opens wider and for longer periods of time, creates less water velocity and turbulence, and provides a gradual transition between fresh and salt water, with salinity refugia available for juvenile fish.

Aluminum and Other Lightweight Materials

One simple way of increasing the amount of time a tide gate is open and consequently reducing its interference with the movement of fish and other aquatic organisms is to make it out of lightweight materials. The lighter the tide gate, the smaller its restorative force, which means that less hydraulic head differential is required to open the gate. A reduction in restorative force implies that the tide gate may be open during every ebb tide, even during seasons when the freshwater flow may be limited and the resulting hydraulic head differential may be small. Equally important, if the tide gate is made from a lightweight material, it will open wider than a heavier one, and such an opening will decrease water velocity and turbulence as water goes past the gate. These various factors combined will improve fish passage conditions (Charland 1998, 2001).

Top-hinged tide gates are now made of aluminum, fiberglass, and plastic (Charland 1998, 2001; Thomson and Associates 1999, 2000). Bates (1999) ran computer simulations to compare two 4-ft-diameter (1.22 m) top-hinged tide gates, one made of cast iron and the other made of aluminum, and estimated that whereas the aluminum gate would open with less than 1 ft (30.5 cm) of hydraulic head differential, the cast iron unit would remain closed. In addition, the opening for the aluminum gate would be 1 ft (30.5 cm) wide. These simulations led him to conclude that the use of aluminum or other lightweight materials to manufacture tide gates could improve fish passage through a top-hinged gate. These results contrast with Charland's (2001) view that top-hinged aluminum gates are not light enough to really make a difference in terms of fish passage.

However, replacing cast iron, top-hinged tide gates with aluminum ones is not the best solution to the problems caused by the traditional kind of gate. First, aluminum gates still close during flood tide, which means that the upstream water-quality problems and the loss of connectivity in the system remain virtually the same. Second, aluminum is not as durable as cast iron when in contact with water. Electrolysis corrodes aluminum more easily than cast iron or steel (especially if a different metal is used in the hinges). The use of "sacrificial" zinc anodes can prevent this, but it increases annual maintenance requirements. Aluminum lids are not as strong as cast iron. Considering that logs and other waterborne debris can break cast iron lids, there is little doubt that floating objects will be able to damage aluminum lids more easily (Charland 2001).

Top-hinged tide gates made of PVC or fiberglass weigh even less, which means that they open under a much smaller hydraulic head differential and open wider than aluminum gates. Another benefit of these types of gates is that their price tag tends to be considerably lower than that of metal gates. Nonetheless, they are not very common. For example, along the Pacific Northwest, Surrey, in southwestern British Columbia, is probably one of the few districts where these lightweight synthetic gates have been installed (Thomson and Associates 1999).

Although PVC and fiberglass gates may offer some improvement over cast iron gates in terms of fish passage, they do not represent a significant improvement for water quality or connectivity to a stream or an estuary. An additional disadvantage of gates made of these synthetic lightweight materials is that they are easily damaged by floating debris and are frequently vandalized. Although all tide gates can be affected by acts of vandalism, fiberglass and plastic ones seem to be so easily damaged that many of them have been destroyed in both Washington (K. Buchanan, Washington Department of Fish and Wildlife, personal communication) and British Columbia (A. Jonsson, Department of Fisheries and Oceans, British Columbia, personal communication).

Radial

The radial tide gate (also called gator gate) is similar to a traditional top-hinged tide gate except that the lid is made from thin, spun aluminum and is concave. Thus, when the tide gate is closed, part of it is inside the culvert. This design produces a lightweight, relatively inexpensive tide gate that weighs only 90 lb (41 kg) (D. Smith, Gator Dock and Marine, Sanford, Florida, personal communication), and, consequently, has a small restorative force, which allows it to open wider under a smaller hydraulic head differential (Charland 1998). This type of tide gate can be best used where cost is an important factor and in areas that are protected from waterborne debris, because its thin lid makes it very vulnerable to damage. With regard to fish passage, this design may prevent the migration of large fish because of the crescent shape of the opening radial tide gates create.

Side-Hinged

The side-hinged design seems to have been developed independently on different occasions. Although hanging tide gates by side-mounted hinges is considered to be a relatively recent improvement in tide gate design, side-hinged tide gates were used in the salt marshes of Guilford, Connecticut, in the mid-1800s (Anisfeld and Benoit 1997). These tide gates were rectangular and made of wood. They were removed in late fall so they wouldn't be damaged when the water froze and were rehung in the spring after the ice was gone (J. Davis, formerly with the East Creek Meadow Owners' Association, Guilford, Connecticut, personal communication).

The side-hinged design was independently rediscovered by Thomas J. Steinke in 1975 (T. J. Steinke, Conservation Department, Fairfield, Connecticut, personal communication) and by Richard Eliasen in 1982 (Anon. 1983; Eliasen 1988). Steinke built and patented a wooden and aluminum side-hinged tide gate while he was investigating design concepts that ultimately led to his invention of the "self-regulating" tide gate. The concept was brought to common use in the 1980s, when Eliasen observed that many top-hinged, cast iron tide gates in British Columbia were not opening as intended during ebb tide. He suggested that if the hinges were placed on the side, the tide gates would open with a smaller hydraulic head differential, remain open for a longer period, and offer a wider opening, which would facilitate fish passage (Anon. 1983; Eliasen 1988). To test his idea, Eliasen had side-mounted hinges attached to traditional round, cast iron tide gates. The test proved his predictions.

Since then, large, side-hinged rectangular doors made of aluminum or stainless steel that are attached to square or rectangular concrete culverts (figure 7) have been developed and are sold commercially. Although these gates can weigh more than a ton, they are hinged so that they can be opened easily with relatively little water pressure from upstream. Some side-hinged gates have been reported to require only one inch of water level difference to open up to 45˚ (Coos Watershed Association, unpublished data). When in use, these doors open wide, and fish passage is expected to be significantly better than when top-hinged tide gates are used (one foot is considered the minimum for adult fish passage by the Washington Department of Fish and Wildlife) (Charland 1998, 2001; Thomson and Associates 1999, 2000).

Because a side-hinged tide gate has no restorative force, the hinges must be installed so the top hinge is closer to the culvert opening than the bottom hinge. This gives the tide gate a slight downward tilt. This tilt creates a restorative force, which enables the tide gate to return to the closed (default) position at the end of the ebb tide (Charland 1998, 2001). The major disadvantage to a side-hinged tide gate is that it is more difficult and costly to build the support structure needed to hang the gate. A side-hinged gate requires precise angles from the vertical, and these must be placed in a structure that will not change its orientation over time and is suspended using strong corrosion-resistant hinges (Charland 2001). If the orientation of the support does change, the door either will not open properly or will not close during flood tide. The angle of tilt must be set with extreme care at the time of installation because any subsequent changes will be very difficult to make.

Although side-hinged tide gates are reported to provide better fish passage, upstream water quality, and estuarine connectivity than the traditional top-hinged gates, neither design can be considered to be entirely fish or environmentally friendly. The basic problem with both types of gates is that they are very good at doing what they were originally conceived for, removing the influence of high tides on upland water levels. Empirical data from con-

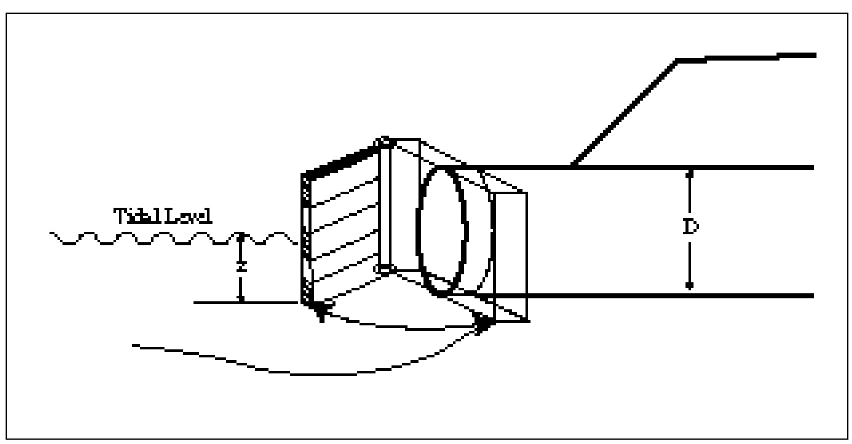


Figure 7. Side-hinged, rectangular tide gate.

trolled comparisons between top-hinged and side-hinged tide gates are needed to establish what degree of environmental improvement side-hinged gates actually cause.

Bottom-Hinged

The bottom-hinged design was also developed and patented by Steinke (T. J. Steinke, personal communication) while he was investigating the concepts that led to his invention of the self-regulating tide gate. The bottom-hinged tide gate was buoyant because it was made of wood and fiberglass. It was hinged at the bottom and had an arm with an adjustable float. The hinging system contained a trip mechanism so that the tide gate would close immediately whenever the float was raised. A single bottom-hinged tide gate was installed and evaluated by Steinke. Because of the trip mechanism, the bottom-hinged tide gate closed every time there was a small fluctuation in water level, including those fluctuations caused by boat wakes. The idea was not pursued after rocks were piled by someone on the gate while it was in the open position, which prevented it from closing.

Rubber Duckbill

The rubber duckbill (also known as Tideflex) is radically different from all other tide gate designs (figure 8). First, it is made of flexible rubber. Second, the opening is a vertical slot in a single molded piece of rubber that fits over the end of a culvert, much like the rubber cap and nipple on a baby's bottle. The vertical opening is flexible but somewhat stiff, and the default position is closed. When the hydraulic head differential is large enough, the vertical slot opens and water flows downstream past the gate. The advantages of this design are not only that the hydraulic head differential needed to open this type of gate is quite small but also, and in contrast to the other types of gates, that debris will not prevent the gate from closing. The flexible nature of the opening allows it to close over debris and form a seal.

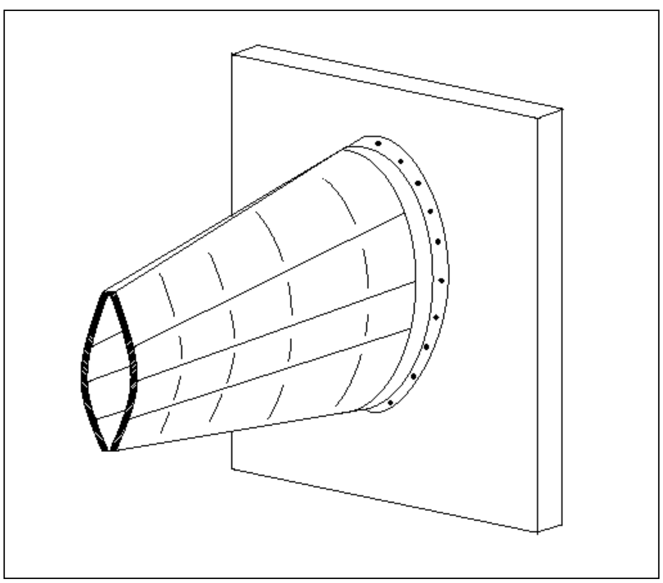


Figure 8. Rubber duckbill.

Because this type of tide gate will open with a small hydraulic head differential, it is assumed that it may allow downstream migration of juvenile salmon (although no evidence was found in the literature to support this). However, it likely prevents upstream migration of adults, so the duckbill should not be classified as a fish-friendly gate design. In addition, by preventing upstream water movement, this gate has other negative side effects on the aquatic environment, such as upstream water-quality degradation and disruption of connectivity between the lower river and the estuary (EPA 1989).

A 4.5 ft (1.32 m) duckbill tide gate was evaluated in a New York City tide gate chamber, and, in terms of downstream flow, it was reported to have performed equal to or better than traditional top-hinged tide gates. It was observed to be self-cleaning when debris was caught in the opening, and there was only minor inflow when the opening closed around debris. In addition, this design was considered to be reliable and low maintenance (Anon. 1989; EPA 1989).

Pet Doors

Several variations on the pet door design were investigated by Charland (1998, 2001). The basic idea is to create a small area (the pet door) within the larger area of a top-hinged tide gate that opens with very low hydraulic head differential to improve water flow and fish passage. Three basic types of pet doors are used on tide gates.

Top-Hinged Pet Door

The top-hinged pet door incorporates a lightweight, top-hinged pet door set into the bottom half of a top-hinged tide gate. Because the pet door is made of a lightweight material (for example, aluminum, plastic) it has a very small restorative force and, therefore, opens as the tide drops before the tide gate itself opens, thus providing fish more opportunity to pass. Water flows downstream through the pet door, and backflow of tide water does not occur. The restorative force of the pet door can be adjusted by adding floats or weights.

This type of tide gate (which is also referred to as a trap door) has been used effectively in the Humbolt Bay area of California for several years, and several top-hinged tide gates with top-hinged pet doors have been installed in Tillamook Bay, Oregon (Charland 1997). Although all gates can be jammed by large pieces of debris, those with pet doors are more susceptible to this kind of problem. The pet doors in the Tillamook Bay area tide gates were damaged by floating debris, and they had to be either replaced or eliminated by welding a metal sheet over the pet door opening (D. Reynolds, Tillamook County Performance Partnership, personal communication; L. Kuntz, Nehalem Marine, personal communication).

Bottom-Hinged Pet Door

In this design, the pet door is hinged at the bottom, and an arm with a float is attached near the upper edge of the pet door's downstream face (figure 9). The major difference between this and a top-hinged pet door is that the buoyancy of the float, not gravity, closes the door. Because it is bottom-hinged, the restorative force is what opens the pet door and, as a result, its default position is open. A bottom-hinged pet door is normally open except when water level on the downstream side of the tide gate rises and closes it by raising the float. One advantage of this type of pet door is that it automatically opens when water level downstream of the gate is below the level of the float, which can be adjusted. This obviously increases the length of time during which water can flow downstream past the gate. The bottom-hinged design also allows some salt water to move upstream through the pet door early in the flood tide, before the float is reached by tide water and the pet door is shut (Charland 1998, 2001).

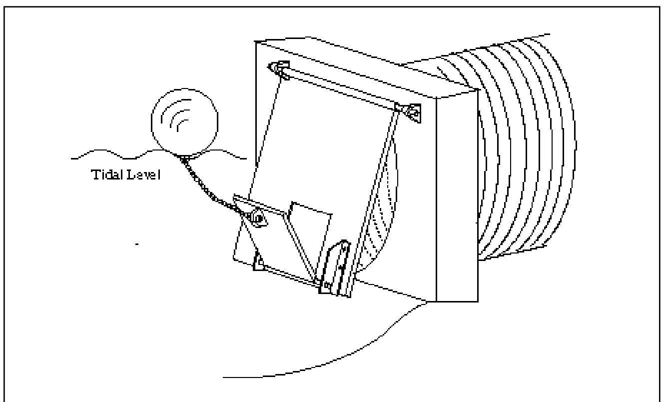


Figure 9. Bottom-hinged pet door.

In theory, a bottom-hinged pet door offers fish and other aquatic organisms more time to move through the gate than does a top-hinged pet door, both upstream and downstream. In addition, upstream water quality is improved and estuarine connectivity is better than with other gate designs because this type of pet door remains open during part of the flood tide (Charland 1998, 2001).

Top-hinged tide gates with bottom-hinged pet doors have been installed in Tillamook Bay, Oregon (Charland 1997). However, as in the case of the tide gates with top-hinged pet doors in Tillamook Bay, the gates with bottom-hinged pet doors failed and were replaced with traditional top-hinged tide gates (D. Reynolds, personal communication).

Side-Hinged Pet Door

The third type of pet door is attached to the tide gate with side hinges. As is the case with a side-hinged tide gate, the pet door is set at a slight angle to the vertical so its default position is closed. Because the angle of the vertical is very small, however, little force is necessary to open the pet door, and it opens easily when water flows down through the culvert. One problem with this type of pet door is that if the tide gate to which it is attached rotates a degree or two, the pet door will not work properly. This design is expected to improve fish passage, but it is less likely to improve upstream water quality or estuarine connectivity.

Permanent Hole

A tide gate with a permanent hole is a variant of the pet door design, except that in this case there is no pet door and the hole is permanently open. Tide gates with a permanent hole may be useful when bidirectional water flow is desired and, at the same time, the amount of upstream salt water must be regulated because of flooding concerns. The permanent hole allows saltwater intrusion, which restores estuarine connectivity, leads to a gradual mix of salt and freshwater, and provides fish with a permanent migration pathway (K. Bates, Washington Department of Fish and Wildlife, personal communication).

This type of tide gate has been used to improve water quality and estuarine connectivity and to control mosquitoes in Australia (Easton and Marshall 2000). A 2.5 in (6 cm) hole was cut in a 29 in (70 cm) tide gate. The Australian lowlands, where these gates have been installed, contain sulfide-loaded sediments that, if exposed to the air and oxidized, can drastically reduce the pH of water. The permanent opening in these gates has improved water quality by raising the pH of water from 2.7 to 6.0, has allowed the migration of three species of fish past the dikes, and has reduced mosquito larvae by over 99%.

This approach to reducing some of the environmental impacts of tide gates is inexpensive. To ensure fish passage, the hole must be large enough and set at the right elevation in the tide gate to avoid producing high water velocities and turbulence as water moves through it.

Self-Regulating, or Buoyant

The self-regulating tide gate (SRT), or buoyant lid, is a variation of the traditional top-hinged tide gate. Its main distinguishing features are the elevated buoyancy of its lid and a set of counterbalancing arms with floats atop the gate (figure 10). Because of its buoyancy, the lid remains open, floating above water, most of the time. This makes this tide gate design different from all others, whose default is the closed position. The open position not only allows upland discharge to flow through the gate during ebb tide (as other gates do), but also allows tidal flushing of the lower reaches of the stream or of the upland wetlands during most of the flood tide cycle. The only

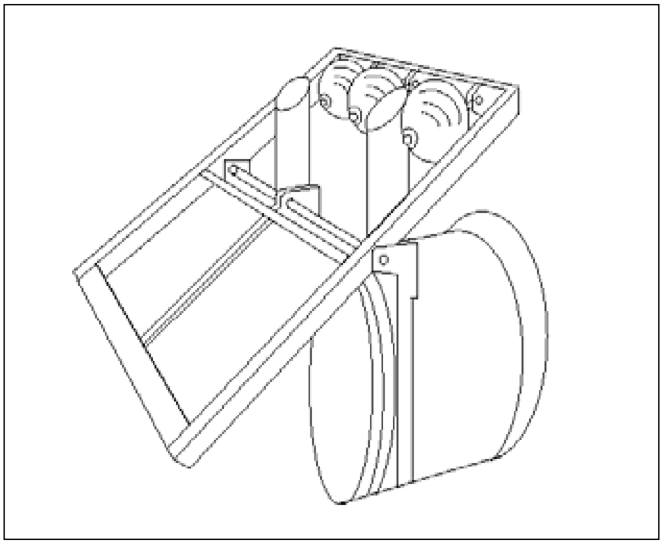


Figure 10. Self-regulating, or buoyant, tide gate.

time this type of gate closes is when flood tides reach a level that is high enough to cause upstream flooding. At that point, the pair of vertical arms with floats is pushed upward and acts as a lever that forces the lid under water, closing the gate. These floats can be adjusted in height to fit site-specific conditions so they close the gate during daily tides or only during extreme tides associated with storm events. Once the tide begins to drop, upward pressure on the floats ceases and the hydraulic head differential in the culvert is able to force the gate to open and allow it to start floating above the receding waters again.

Waterman Industries, Inc., which manufactures this type of gate and sells it under the name Waterman/Nekton, claims that it restores estuarine plants, fish, shellfish, waterfowl, and wildlife habitat; reestablishes tidal flushing of marshes without flooding of upland property; reduces mosquito breeding areas by natural means; and deepens both upstream and downstream channels, which improves drainage. Considering that self-regulating tide gates are designed to remain open most of the time, they are likely to produce these benefits and improve fish passage greatly.

In the state of Washington, when a tide gate needs replacing, the Department of Fish and Wildlife would like it to be replaced with a self-regulating tide gate or with one that functions in a similar manner (K. Bates, personal communication).

Self-regulating tide gates have been used to restore tidal flushing in several marshes on the Connecticut shore of Long Island Sound. These tide gates have been very successful in restoring estuarine connectivity, which is the first step in restoration. When saltwater intrusion was restored during high tide, significant ecological changes were noted within a single growing season: freshwater plants died, and salt-tolerant marsh plants replaced the freshwater invaders (Roman et al. 1984). This type of tide gate was also installed in Montezuma Slough, in the San Francisco Bay area, where it seems to have functioned well and improved fish passage, depending on the setting. One important disadvantage that has been noted is that the floats collect debris, which requires frequent maintenance (J. Haltiner, Phillip Williams and Associates, personal communication). Keeping the floats free of debris is crucial for the good operation of this type of tide gate.

Mitigator Fish-Passage Device

The mitigator fish passage device was invented by Leo Kuntz (with Nehalem Marine). It is normally part of a top-hinged tide gate that is kept open during part or all of a flood tide by the mitigator device. The tide gate is top-hinged, round, and made of aluminum (figure 11). It is double hinged, and the second set of hinges is attached to the tide gate at about one-third of the distance from the top edge. The double hinging, coupled with a relatively small restorative force—a 4 ft (1.22 m) tide gate weighs 90 pounds (41 kg)—causes the tide gate to open with only 0.5 in (1.2 cm) of hydraulic head differential. It opens immediately to 20° (L. Kuntz, personal communication).

What makes this tide gate different from other traditional top-hinged tide gates is the mitigator fish-passage device that is attached to the tide gate (figure 11). The mitigator fish-passage device is a float-operated, cam-lock system that prevents the tide gate from closing during part or all of a flood tide. During an ebb tide, the float arm drops when the water level in the estuary drops. When this occurs, it rotates a set of cams, which look somewhat like semicircles, and the flat sides face down. The cams

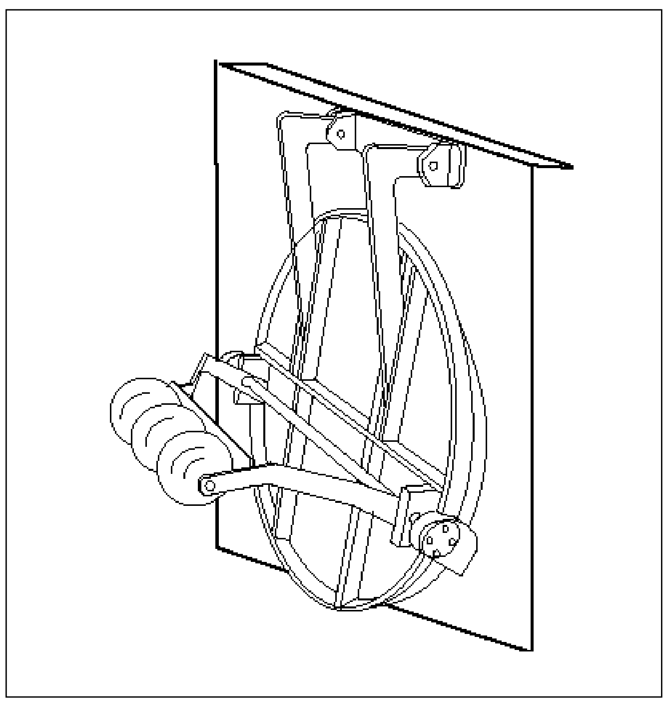


Figure 11. Mitigator fish-passage device.

have a small flat spot, which locks the cams into place when they are pressed against the faceplate to which the tide gate is attached. When the tide gate closes at the end of the ebb tide, the cams prevent the tide gate from closing completely, and the bottom of the gate opens up to 8 in (20 cm). This allows brackish water to move upstream past the tide gate. As the water level rises, the top part of the tide gate closes, but the bottom remains open 8 in (20 cm) until the flood tide forces the float arm past a certain point that rotates the cams and allows the door to close normally. This allows the tide gate to close (L. Kuntz, personal communication).

This design was intended to restore connectivity and allow smolts to migrate past the tide gate during flood tide so they could use sloughs and wetlands that had been isolated. Adult migration into these "dead end" habitats was not desired, because they contain no spawning areas and there is no access to spawning areas. The 8 in (20 cm) opening during the initial stages of flood tide prevents adults from migrating past the tide gate. However, if adult passage is desired, larger cams could be installed, and that would increase the size of the opening during the initial stages of flood tide (L. Kuntz, personal communication).

This type of tide gate has been installed in several locations along the Columbia River and in the Nestucca and Tillamook Bay areas of Oregon, and it has restored connectivity and allowed juvenile salmon to use estuarine areas that had been isolated for years by traditional tide gates (Anon. 2000; L. Kuntz, personal communication).

Muted Tide Regulator

A further progression in tide gate design by Leo Kuntz of Nehalem Marine is the muted tide regulator (MTR) (patent pending). This design is similar to that of the mitigator fish passage device and the self-regulating tide gate in that it allows flood tides to enter past the gate (figure 12). The innovation in the MTR is that its closing is regulated by the elevation of the inlet pool, as opposed to the tidal elevations in the mitigator and SRT gates. Using the elevation of the inlet pool adds additional functionality to the gate because it can respond to, and control, inlet pool elevations resulting from upstream freshwater, as well as tidal, inflows.

The closing of the tide gate in the MTR is controlled by a float in the inlet pool attached to a control mechanism that extends to the tide gate. A control arm is hinged at the float but has a fixed vertical riser on the shore side that is hinged at its base (figure 12). As the float rises and falls with the elevation of the inlet pool, a control rod connected to the tide gate side is pushed (rising pool) or pulled (falling pool). On the tide gate, a mechanism similar to the float (that is, a vertical riser hinged at the base and attached to the tide gate) responds to the push and pull of the control rod by opening or closing the gate. However, in the MTR the tide gate also opens when tidal elevations are less than the elevation of the inlet pool, if drainage is desired during low tides or during high freshwater inflows.

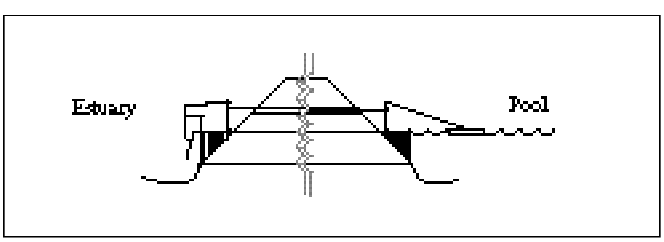


Figure 12. Muted tide regulator.

The primary advantage of the MTR is its ability to respond to freshwater inflows while still allowing tidal exchange to occur. This overcomes a significant limitation in both the mitigator and SRT designs, which respond only to tidal levels. By incorporating pool elevations in the control mechanism, the MTR should be able to regulate more precisely the upper range of the pool. This, in turn, should allow for a more extensive opening period because the uncertainty of unexpected inflows will not need to be taken into account in setting the closing point, as is the case with the mitigator and SRT designs. Allowing the maximum extent of the backwater pool will enhance mixing of brackish and fresh waters, increase connectivity between the estuary and areas behind the gate, and provide for greater potential rearing habitat for salmonids and other aquatic organisms.

The first MTR tide gate will be installed in the Humbolt Bay, California, National Wildlife Refuge in the winter of 2004–2005. Additional installations are expected in Tillamook and Coos Bay, Oregon, in 2005. Performance data for the MTR design have not been established to date.

Manually Operated

The manually operated tide gate is not a type of tide gate; it is a type of tide gate management. It is simply an alternative way of managing a tide gate so that its operation simulates that of a self-regulating tide gate. In this case, the tide gate is propped open, and it is closed only during the winter months or when high tides that are capable of causing flooding are predicted to occur. Another alternative is to add a sluice gate mechanism (like a guillotine) to a standard tide gate, which allows the entire gate to be raised out of the way of the culvert for months (Charland 1998).

It is possible to operate these gates with an electrical motor and to activate them remotely. If this is done, the tide gate should be monitored to ensure it is working and in the proper position. If electrical power is disrupted early during a storm, the tide gate might not close, and this could result in upstream flooding.

Keeping the gates open or removed from the culverts for extended periods of time will improve connectivity, upstream water quality, and fish migration. Many tide gates were installed to protect against flooding caused by extreme high tides. Because this level of protection is not needed all the time, the manual closing of tide gates only when high tides are anticipated will provide upstream flood protection without any of the negative effects associated with regular tide gate operation.

Manually controlled top-hinged tide gates were used to restore many of the Florida marshes that had been diked for mosquito control. The tide gates were kept open fall and winter and were closed and allowed to operate as tide gates mid-April to September (Carlson 1987). This management protocol, called rotational impoundment management, has controlled mosquito populations while allowing fish to use those habitats. A similar management approach has been used in the Skagit River Delta, Washington, where a tide gate is kept open nine months of the year (Beamer and LaRock 1998). In the winter months it can be closed during a predicted flood event, and it is monitored regularly to make sure it is in the proper position. This operational protocol has improved water quality, connectivity, and fish passage to some extent (E. Beamer, Skagit System Cooperative, personal communication). However, adult coho, fall chinook, chum, pink salmon, winter steelhead, and cutthroat trout return to their natal streams in the fall and winter, when flood tides tend to be at their highest and both self-regulating and manually operated tide gates are closed. Because of this possible interference with winter fish movement, they cannot be considered entirely fish friendly.

A different type of manually operated tide gate has the top-hinged pet door design, but the pet door is quite large in proportion to the gate and remains open most of the time. To improve water flow and connectivity in the Skipanon River, Warrenton, Oregon, a 3 ft x 4 ft (0.92 x 1.22 m) opening was cut in the lower third of each of three 8 ft x 10 ft (2.44 x 3.05 m) top-hinged, wooden tide gates. Each opening was covered with a manually operated top-hinged lid. Before these manually operated pet doors were added to the tide gates, water above the gates was stagnant, contained dense algae blooms, and had emergent freshwater plants, and neighbors complained about the smell of decomposition gases. After these manual pet doors were in place, upstream water changed from green and opaque to blue and clear, algal blooms and emergent plants disappeared, and foul-smelling gases were no longer detected. Additionally, fish passage appears to have improved, as salmon are now observed on the upstream side of the tide gates (T. Cullison, Columbia River Estuary Task Force, personal communication).

Reversed Fishway

A different approach to fish passage problems is proposed by D. Porior (Porior Engineering, personal communication) who has designed a “reversed fishway” that is installed in the proximity of a tide gate. Porior’s reversed fishway resembles a culvert set into the dike at an angle with its high end facing the estuary. The slope of this fishway depends on the width of the dike and the anticipated height of flood tide water. In this fishway, water enters during flood tides and flows upstream past a series of baffles, thus allowing upstream and downstream fish passage when the adjacent tide gate is closed.

Legal Framework

Although many tide gate replacement projects are carried out by governmental agencies, sometimes watershed councils or individuals may be interested in carrying out this type of project. In those cases, it is important to acknowledge the existence of a detailed permitting process that needs to be initiated well before the installation, repair, modification, replacement, or removal of tide gates can begin.

A comprehensive listing of all laws and regulations that apply to tide gates is beyond the scope of this publication. In the United States there are both federal and state laws, as well as different types of regulations and guidelines, that control tide gate installation, replacement, and operation. Cylinder at al. (Cylinder et al. 1995) compiled and explained federal and state laws and regulations that pertain to wetlands in California in a 363-page book.

Appendix 2 includes a summary of U.S. and Canadian laws and regulations that are intended to regulate the installation, operation, and replacement of tide gates.

Discussion and Conclusions

An increasing number of scientists, resource managers, regulators, and members of the public are beginning to recognize the importance of estuaries and sloughs and of the tidally influenced portions of rivers as fish and shellfish habitats and as corridors to other habitats. They have begun to realize the extent to which the undesirable physical, chemical, and biological side effects of tidal flow restriction by dikes and tide gates influence the survival and production of wild stocks of anadromous salmon and trout. As a result, the protection and restoration of these ecosystems have finally appeared on the radar screen of many regulatory agencies and nongovernmental organizations.

In the particular context of salmon habitat restoration and enhancement efforts that have been underway in western North America for more than two decades, the scarce attention that estuarine habitats have received is perplexing. This inattention implies that the unimpeded migration of fish between their spawning and rearing freshwater habitats and the vast ocean feeding grounds, or the acclimation and nursery role these transitional brackish water environments play, is unimportant to the continued existence of salmon and trout populations. Salmon management and enhancement programs need to consider as tightly interconnected units the freshwater, estuarine, and marine ecosystems used by salmon and trout during their entire life cycle. Unfavorable conditions for salmon and trout in any one of these three ecosystems will affect the survival and abundance of their populations. Because many dikes and tide gates interfere with both adult and juvenile migration and estuarine habitat use, efforts to remove or replace those tide gates that impede fish passage should receive higher priority than they have so far. Functioning estuarine wetlands also provide large influxes of carbon and nutrients to the estuarine system, benefiting even those species and individuals not directly residing in the marshes.

Every tide gate removal or replacement project is unique and its results will depend on a myriad of factors. Hence, before embarking on a tide gate removal or replacement project, we need thorough habitat and hydrological studies to ensure that the desired outcomes can be achieved. In some instances tide gate removal as a means of restoring wetlands could be counterproductive if it produces water-quality problems, such as oxygen depletion or acidification (Coats et al. 1989; Roman et al. 1995). In other cases, the improved upland draining that results from tide gate replacement may reduce the availability of some type of habitat that formed after the construction of the dike and that is being used by some species of special interest or concern. In any case, before a tide gate is removed, the upper reaches of the new water boundary must be carefully determined to avoid the unintended flooding of property. High-resolution GIS maps can be used to delineate the upper extent of tidal inundation.

It is important to understand that dikes and their tide gates, regardless of how fish friendly their design and operation is, will always interfere with fish movement and alter the quality of their habitats. In particular, tidal marshes are most affected, both by changes in the amount and timing of flow in their channels and by the interruption of sheet (nonchannelized) tidal inflow. Where fish habitat degradation and loss above dikes is severe, tide gate replacement to improve fish passage should not be considered an option. Fish may become trapped for some time above the dike and be exposed to unfavorable habitat conditions (that is, high water temperatures, low levels of dissolved oxygen, high predation rates). Even tide gates that remain open most of the year, when flooding is not of concern, and are closed only during the winter high tides are expected to affect juvenile salmonids that seek to use tidal marsh channels year round. Hence, a completely fish-friendly tide gate design or operation regime does not exist. However, in many locations along our coast, there are opportunities for habitat quality and fish-passage improvement if, after the necessary evaluation, tide gates are either removed or replaced with the appropriate type of design and setting.

A first step in determining the extent of the environmental effects of tide gates and dikes in the estuarine habitats and salmonid populations of western North America is to conduct a complete inventory of these structures. In British Columbia, these data are available for each of almost 300 diking districts, but a single master document that compiles this information does not exist (D. R. Finlay, Ministry of Air, Water, and Lands, British Columbia, personal communication). It is estimated that there are 500 tide gates in the lower mainland of British Columbia; 200 of them are in the Surrey Diking District alone (Thomson and Associates 1999).

Interviews with several watershed council coordinators in Oregon revealed that most of them do not have a complete list of all the tide gates in their watersheds. In Oregon, HB3002, which became a law in 2001, requires the Oregon Department of Fish and Wildlife to compile such an inventory, and according to C. Corrarino (Oregon Department of Fish and Wildlife, personal communication), one is under way. Staff with the Washington Department of Fish and Wildlife also indicated to us that a tide gate census is being planned for Washington (K. Bates, personal communication).

These tide gate surveys should include supplementary information (that is, tide gate size, type, condition, and habitat potential) that will help evaluate the overall impact of these structures and could be used in prioritizing removal or replacement projects. Charland's (1997) survey of tide gates in the Tillamook Bay area of Oregon can be used as a template for this kind of work. The Tillamook County Performance Partnership has built upon Charland's survey. The Partnership, which works with landowners and local drainage districts, has identified many additional tide gates and mapped their location using GIS (Geographic Information Systems) (R. Felley, Tillamook County Performance Partnership, personal communication).

Each surveyed tide gate should be closely evaluated to identify any damage and determine its working condition. In some cases, gates will need to be observed during at least part of a tide cycle to determine their condition. All tide gates, and in particular those in questionable shape, should be subjected to regular inspections. Although tide gates are designed to be low-maintenance devices, they tend to jam with debris, their hinges tend to break or corrode, and they can be vandalized or even damaged by nutria, which can chew into the rubber or neoprene gaskets between the upstream side of a tide gate and the culvert (L. Kuntz, personal communication).

Finally, it will be important to assess the effects each tide gate might have on the surrounding environment. This can often be done by monitoring key water-quality variables, such as salinity, temperature, and dissolved oxygen, on both sides of the gate. The presence and type of aquatic vegetation upstream from the gate is another important indicator, which in combination with the water-quality data could help determine to what extent the operation of the tide gate has disrupted the connectivity of the system and degraded the aquatic habitats that fish may have access to. Although the effects on fish passage may be estimated in general terms based on parameters such as opening size, duration and frequency, and water velocity through the opening and turbulence, direct observations during both juvenile and adult salmonid migrations are recommended to obtain conclusive evidence. In general, however, it can be assumed that most tide gates will affect fish movement. Traditional cast iron, top-hinged tide gates are very likely to act as barriers to salmon and trout migration; and even fish-friendlier designs (for example, self-regulating, side hinged, and permanent hole) are unlikely to be totally free of impacts.

This information could be used to produce a list of tide gates that should be repaired or replaced. Except for those instances when fish passage above a tide gate might not be desired (that is, lack of adequate fish habitat above the dike), most traditional top-hinged tide gates may need to be replaced by some fish-friendlier design to improve fish access and utilization of both freshwater and estuarine habitats. In some cases, changes in tide gate management or top-hinged tide gates that can be propped open for most of the year may be considered (bearing in mind that they will impede salmonid access to critical nursery habitats during high tide periods).

Regulatory agencies and watershed councils interested in tide gate monitoring and replacement should develop a set of criteria for prioritizing their tide gate removal or replacement projects. Examples of such criteria are impediment to juvenile fish passage, impediment to adult fish passage, presence of threatened or endangered species, water-quality degradation, creation of conditions that favor exotic species, present need for control of tidal flooding, loss or degradation of upland wildlife habitat, reduction of channel depth and upland drainage, and barriers to navigation (that is, recreational). After the completion of an impact evaluation, those tide gates that are identified as having the greatest negative and reversible effects on fish and the environment and that are located in either public land or within the property of a cooperating landowner should receive the highest priority for removal or replacement.

Despite the relatively restricted coastal location of tide gates, the removal or replacement of the gates must be considered always from a watershed or ecosystem perspective. This entails analyzing the benefits and negative effects of the project looking beyond its adjacent channel reach and taking into consideration upstream habitat quality, sediment and detritus transport processes, the effect of brackish and freshwater exchange on marsh vegetation, and other factors affecting water quality and fish passage in the system. As for any habitat improvement project, it is important to identify clear goals, set realistic time lines, and select monitoring variables and techniques that will allow its evaluation. Useful guidelines regarding the planning that is needed before a habitat improvement project begins are provided by Coats et al. (1989), Dreyer and Niering (1995), and Burdick et al. (1997).

Choosing a Replacement Tide Gate

Once it has been decided that the replacement of a tide gate is warranted, a new gate has to be chosen. That selection process should be guided by the goals that were developed for the project, which usually include improving fish passage, water quality, and habitat connectivity. In the absence of independently conducted field evaluations comparing the environmental and fish friendliness of the different new tide gate designs, such selection might not be a simple task.

Fish-passage improvement (or fish friendliness) has been the main trait attributed to most of the new tide gate designs. However, their performance in this area has not been standardized in any way, and perhaps a range of the percentage of time (for example, 60% to 80% of the time) each gate type is anticipated to allow fish passage—under the best and worst conditions—could be used as one of the metrics needed to determine its degree of fish friendliness. The value of other important metrics (water velocity and depth, turbulence, minimum opening size, and so on) may depend on the location and installation of the tide gate. Such values have been derived for culverts (see "Culverts") and could be used as a good first approximation to evaluate how fish friendly a tide gate type is.

Although tide gate setting will determine its operation and effects on fish movement, among the current designs, the self-regulating, or buoyant, gate, the muted tide regulator, the top-hinged gate with a mitigator fish passage device, and the gate with a permanent hole appear to be the most fish-friendly ones. These models are likely to be followed, in terms of fish friendliness, by side-hinged tide gates. The self-regulating gate is likely to interfere the least with fish movement because, in contrast to the other types of gates, its default position is open. The only time migration is impeded is during extremely high flood tides. Additionally, one would also anticipate finding better habitat connectivity and upstream water quality with this type of tide gate than with others. Similar results could be achieved with manually operated tide gates if they were left open most of the time. Instead of reduction of the tidal range, the aim should be to obtain the shortest possible disruption of tidal inundation in terms of days, not months (that is, the entire winter).

According to L. Kunz (personal communication), the top-hinged tide gate with a mitigator fish passage device is more fish friendly than traditional gates because the cams keep the tide gate ajar during part or all of the flood tide, allowing juvenile fish to migrate through. Adult passage might be achieved by increasing the size of the cams.

It should be noted that this tentative ranking of gate designs does not imply the endorsement of any one of them in particular. It is a simple categorization based on the way each type of gate is expected to operate under normal circumstances, according to various reports, information made available by the manufacturers, and anecdotal information gathered in Oregon and British Columbia during the production of this report. We did not find any empirical studies comparing the performance of different types of tide gates under similar conditions. Consequently, selecting one of the new gate designs over the others should not be done on the basis of this report, but after site-specific consultations with hydrologists and fish passage experts. The promising muted tide regulator had not been installed at the time this report was completed and, as a result, field performance data were not available.

Future Directions

Gray et al. (2002) recently assessed the response of juvenile chinook salmon to the removal of dikes in the Salmon River Estuary, and Thomson and Associates (2000) compiled information on the effects of tide gates on adult fish migration in tributaries of the Lower Fraser River. However, we failed to find any studies that either looked at the effects of tide gates on juvenile fish or directly compared how the different designs affected fish passage. This constitutes a critical knowledge gap for resource managers. Based on the evidence available from Tillamook Bay, where Charland (1997) surveyed 49 tide gates, from other Oregon and Washington estuaries (that is, Coos Bay, Yaquina Bay, Columbia River estuary, Willapa Bay, Grays Harbor, and Puget Sound) (J. Kelly, Oregon Department of Fish and Wildlife, personal communication), and from the many diking districts in British Columbia, it is likely that the number of tide gates in the western coast of North America reaches well into the hundreds if not the thousands. Moreover, the situation is likely only to worsen as more tide gates are installed in response to rising sea levels caused by global climate change.

Because many adult salmon and trout enter their natal streams in the fall and winter, it is feasible that the migration of some stocks is blocked by even the self-regulating or the manually operated tide gates. We could not find any study that looked into that potential problem. A better understanding of fish migratory patterns in estuaries and tidally influenced habitats would be of great value in developing even fish-friendlier tide gates. Levy et al. (1979) studied juvenile salmon migration in tidal channels in the Fraser River estuary, British Columbia, and they found that pink salmon migrated at the beginning of the ebb tide, chum salmon near the middle of the ebb tide, and chinook salmon during the latter stages of the ebb tide. Consequently, pink salmon and chinook salmon will be more affected than chum salmon by the normal tide gate opening and closing cycles when hydraulic head differential is small. Studies like this, but which are focused on the specific tide cycle stages that both juvenile and adult salmon and sea-run trout choose to enter flood boxes, would be very valuable in helping design truly fish-friendly gates. A study of timing, use, and growth of juvenile chinook salmon in paired gated and natural marshes would provide a broader perspective on the effect of tide gates on the performance of salmon in an altered system. Local populations of chum, pink, and chinook salmon may also be most affected by a reduction in access to lower river and estuarine tributaries.

The need to understand the effects of tide gates on estuarine habitats and on salmon populations is further accentuated by the current investment of limited public funds in the replacement of old tide gates by new ones as part of habitat enhancement projects. These projects would benefit from having adequate empirical information on the performance of the supposedly fish-friendly tide gate designs that are being installed. Carefully planned field studies and effective monitoring programs are needed to establish what types of tide gates are most effective at maintaining unimpeded fish passage, estuarine connectivity, and high water quality.

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Appendix 1: Manufacturers

Although the list of tide gate manufacturing firms provided below is the result of a thorough search, it may be incomplete. It was not possible for the authors to ensure that all firms that manufacture tide gates either within the United State of America or abroad were identified during the preparation of this report. In addition, the inclusion of a manufacturing company in this list does not imply any endorsement by the authors of the company or any of its products and services.

Armtec
15 Campbell Road
P.O. Box 3000
Guelph, Ontario N1H 6P2 Canada
Phone: 519-822-1160
Fax: 519-822-1160
www.armtec.com
e-mail: usa@armtec.com
Armtec makes top-hinged, round, cast iron tide gates; aluminum side-hinged, square (rectangular) tide gates; and sluice gates.

Dos-Ir Gates and Valves
1465 250th Street
Libertyville, Iowa 52567-8523
Phone: 641-693-3311
Fax: 641-693-4131
www.dosir.com
e-mail: dosir@lisco.com
Dos-Ir makes top-hinged tide gates from PVC and fiberglass reinforced with aluminum.

Gator Dock and Marine, Inc.
2880 Mellonville Ave.
Sanford, Florida 32773
Phone: 800-621-2207
Fax: 407-322-6574
www.gatordock.com
e-mail: piling@gatordock.com
Gator Dock and Marine makes the concave, radial tide gate (Gator Gate®).

Golden Harvest, Inc
P.O. Box 287
Burlington, Washington 98233
Phone: 800-338-6238
Fax: 360-757-1135
www.goldenharvestinc.com
e-mail: ghi@goldenharvestinc.com
Golden Harvest makes top-hinged, round tide gates from cast iron and aluminum. They have also built gates with pet doors.

Nehalem Marine
24755 Miami River Road
Nehalem, Oregon 97131
Phone: 503-322-0265
Fax: 503-322-0211
No Web site
e-mail: nmarine@oregoncoast.com
Nehalem Marine makes top-hinged, round, aluminum tide gates with and without a mitigator fish passage device.

Plasti-Fab, Inc.
P.O. Box 100
Tualatin, Oregon 97062
Phone: 503-692-5460
Fax: 503-692-1145
www.plasti-fab.com
e-mail sales@plasti-fab.com
Plasti-Fab makes flexible rubber tide gates.

Red Valve
700 N. Bell Ave.
P.O. Box 548
Carnegie, Pennsylvania 15106-0548
Phone: 412-279-0044
Fax: 412-279-7878
www.redvalve.com
e-mail: valves@redvalve.com
Red Valve makes duckbill (or Tideflex) tide gates.

Rodney Hunt Co.
Orange, Massachusetts 01364
Phone: 800-448-8860
Fax: 978-544-7209
www.rodneyhunt.com
e-mail: rh@hodneyhunt.com
Rodney Hunt makes top-hinged, round tide gates.

Waterman
P.O. Box 458
Exeter, California 93221
Phone: 559-562-4000
Fax: 559-562-2277
www.watermanusa.com
e-mail: watermn@watermanusa.com
Waterman makes top-hinged, round tide gates out of cast iron, steel, or aluminum; square (rectangular), top-hinged tide gates out of cast iron, wood, or aluminum; sluice gates; and the self-regulating type of gate.

Appendix 2: Laws and Regulations

United States Federal Laws

Several federal laws, enforced by various agencies from the U.S. Departments of Defense, Interior, Commerce, and Agriculture, regulate the use of tide gates. The following U.S. laws are relevant to tide gate installation, operation, and replacement.

Section 404 of the Clean Water Act

Section 404 of the Clean Water Act regulates construction activities that involve dredging or filling in U.S. waters. Its enforcement is overseen by the Army Corps of Engineers, but the Environmental Protection Agency is charged with developing regulations and reviewing projects that have been permitted by the Army Corps of Engineers. Consequently, any structure that might alter a natural body of water (both tidally influenced brackish water and freshwater) or even some artificial bodies of water is covered under this law. The law does not apply to wetlands that were converted to agricultural lands before December 23, 1985, if these lands no longer exhibit wetland characteristics. Additionally, normal farming and silviculture activities are exempt.

Section 10 of the Rivers and Harbors Act of 1899

Section 10 of the Rivers and Harbors Act of 1899 regulates all construction work done in, over, or under navigable waters or that excavates or deposits material into what are deemed to be navigable waters in the U.S. Navigable water is defined as any water that has historically been used for or could possibly be used for transportation of interstate commerce. If this determination is made for a portion of a given body of water, the law applies to the entire body of water. This law can be applied even to water no longer considered navigable because of levees or other alterations that were permitted in the past. The enforcement of this law is overseen by the Army Corps of Engineers.

Flood Control Act of 1936

The Flood Control Act of 1936 directs federal agencies to manage the environment and to alter it if necessary to prevent flooding. It is overseen by the Army Corps of Engineers.

Clean Water Act

A component of the Federal Water Pollution Control Act, the Clean Water Act regulates all activities that might disturb or pollute natural bodies of water. The law requires that anyone who wants to dredge in or deposit material into U.S. waters must obtain a permit from the Army Corps of Engineers. The enforcement of this law is overseen by the Environmental Protection Agency and the Army Corps of Engineers.

Coastal Zone Management Act

The Coastal Zone Management Act creates a program of land development control in coastal areas that incorporates state and federal laws. Consequently, it can be slightly different for each state. Proposed projects for a coastal area must be compatible with coastal zone rules and laws. This law is implemented by the Army Corps of Engineers.

Fish and Wildlife Coordination Act

The Fish and Wildlife Coordination Act calls for comments and reviews by the Fish and Wildlife Service and by NOAA Fisheries (the National Marine Fisheries Service), and it gives them potential veto authority over any federal program that could modify a natural body of water in the U.S., even those permitted by other federal agencies. Consequently, this law can be used to veto projects approved by the Army Corps of Engineers under Section 404 or Section 10. This law is enforced by the Fish and Wildlife Service and NOAA Fisheries.

National Environmental Policy Act

The National Environmental Policy Act calls for comments and reviews on how a federal program could affect the human environment—how it will affect society as a whole, what interest groups would be affected, and how it will affect a locality. This assessment also needs to include possible mitigation efforts that might be used to reduce the severity of any problem caused by the program. The law is administered by the Fish and Wildlife Service and by NOAA Fisheries, and it gives them potential veto authority over any federal project that might be done in any natural body of water in the U.S. Consequently, this law can be used to veto projects approved by the Army Corps of Engineers under Section 404 or Section 10.

Endangered Species Act

The Endangered Species Act requires that all federal agencies ensure that any activity that can adversely affect a threatened or endangered species, either directly or indirectly, be modified or forbidden. Since a number of salmon stocks already have been designated as threatened or endangered, human-made objects that can affect these stocks must be managed to prevent adverse effects. In the case of tide gates, this should mean that fish passage should not be impeded. This law is regulated by both the Fish and Wildlife Service and NOAA Fisheries.

Food Security Act of 1985

The Food Security Act of 1985 penalizes farmers who plant commodities on wetlands that have been filled, drained, or converted from brackish water wetlands to agricultural lands. Inadvertent draining of wetlands is also forbidden; if this occurs, the farmer must restore the land to its original state. This law is enforced by the Department of Agriculture. The Food Security Act contains a provision called the Conservation Reserve Program that pays farmers to stop farming converted wetlands and to help reconvert these fields into wetlands.

Oregon State Law

In 2001, the state legislature passed and the governor signed a new fish-passage statute, HB 3002 (ORS 509.580-509.645). This law supercedes other Oregon laws and regulations that concern fish passage in state waters. The new law also repealed some Oregon statutes that had been used to regulate fish passage. The law provides that the Oregon Department of Fish and Wildlife enact new regulations concerning fish passage and empowers it to convene a fish-passage task force to develop rules associated with the new statutes.

HB 3002 now requires both upstream and downstream fish passage at all human-made obstructions in waters where migratory native species of fish currently live or have existed historically. The law does not increase enforcement orders but seeks to implement the policy through cooperation with those who own or operate the obstructions. However, construction projects, abandonment of an obstruction, or a change in permit status can trigger the requirement for fish passage. Additionally, the law empowers the Fish and Wildlife Commission with the emergency authority to install fish passage devices at an owner's expense if a native migratory population is adversely affected by an obstruction.

HB 3002 also repeals ORS 498.351 and 509.605, which governed the passage of anadromous, game, and food fish at artificial obstructions, such as culverts. In brief, those rules recommended that 100% of migrating fish should be able to migrate through or around an obstruction 90% of the time during normal migratory periods. Even though these rules applied to tide gates, such passage standards could not be accomplished by traditional top-hinged tide gates. HB 3002 does not set specific rules for fish passage. Instead, it directs the Oregon Department of Fish and Wildlife to develop general rules for fish passage.

HB 3002 requires the Oregon Department of Fish and Wildlife to complete a statewide inventory of all artificial obstructions, which means a complete inventory of all tide gates in Oregon. Such an inventory was proposed in 1997 (Mirati 1997), but it was not conducted. The inventory should also include an evaluation of how each tide gate affects fish passage and how it alters habitat. Additionally, the inventory should include recommendations about mitigation efforts that would be needed to improve or restore fish passage at each obstruction. Once the inventory is completed, mitigation efforts should be prioritized.

Washington State Law

In Washington State, two laws, RCW 77.12.047 and RCW 77.55.100, and one regulation, WAC 220-110-07, govern fish passage in general. However, tide gates are not explicitly mentioned in them. RCW 77.12.047 stipulates that Washington State laws must be commensurate with and consistent with federal laws. RCW 77.55.100 stipulates that any project that alters a natural body of water must ensure that fish are not harmed in any way; this includes fish passage. WAC 220-100-070 prescribes what is necessary for fish passage. Although it specifically discusses what is needed for adult anadromous fish passage through culverts, the same criteria apply to tide gates. Fish passage for juvenile anadromous fish is not listed.

Canadian Law

The Fisheries Act of Canada is the Canadian law that governs tide gates in Canada. This law consists of many sections that regulate activities that can have adverse effects on wild stocks of fish in Canada. Other sections list agencies that are in charge of regulating the law or prescribe penalties for those who violate the law. Following are the sections of the Fisheries Act most germane to tide gates:

- Section 20 provides that human-made structures should not obstruct fish passage, and if they do, mitigation must be provided to ensure proper migration around the obstruction.
- Section 21 requires that unused obstructions that prevent fish migration be removed, or mitigation efforts must be done to facilitate migration around the structure.
- Section 22 requires that minimum flow rates be required through or around an obstruction in a body of water so normal fish migration can occur.
- Section 29 says that no structure can be erected or maintained in a body of water if it obstructs the passage of fish.
- Section 35 says that no construction can be undertaken if the project will alter or destroy fish habitat.