Coastal Resource Planning within the Klamath River Estuary
Task 3 (Spit Assessment): Summary Report

Prepared for the Yurok Tribe, Klamath, California, USA

Prepared by:
Jeremy P. Lowe and Rowyn D. Cooper-Caroselli, Wolf Water Resources, Portland, Oregon, USA

Laura S. Brophy and Roger N. Fuller, Estuary Technical Group, Institute for Applied Ecology,
Corvallis, Oregon, USA

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Project context

This report constitutes the deliverable for Task 3 ("Assessment of the Klamath Estuary Spit") in the Estuary Technical Group's (ETG's) contract with the Yurok Tribe executed April 18, 2016. The contracts' goal is for ETG to assist the Tribe with coastal resource and climate change adaptation planning for the Klamath River Estuary.

The original Scope of Work developed by the Tribe for the contract focused strongly on recommendations for improvements to the "Sea Level Affecting Marshes Model" ("SLAMM") for the Klamath River Estuary. However, during the kick-off meeting in May 2016, the Tribe expressed its interest in thinking more broadly about ways to approach potential impacts of climate change to the estuary, rather than focusing on SLAMM. In subsequent discussions with the Tribe this was re-emphasized. For example, rather than developing data recommendations specifically to improve SLAMM as described in Task 1 ("Data and Model Review"), it was agreed that the ETG team would deliver broader data recommendations for improving the Tribe's ability to understand potential estuary habitat responses to climate change. These recommendations would constitute a combined deliverable for Tasks 1 and 2 (Task 2: "Data recommendations") which would be delivered after the Tribe's planned Klamath Estuary Workshop to be held in January 2018. As an initial step towards this combined deliverable, the ETG team delivered monitoring recommendations on July 7, 2016. Results of the recommended monitoring would support the Tribe's climate change adaptation planning in several ways: for example, the results could be used to support development of estuary habitat maps and models (including SLAMM if desired), and to improve general understanding of estuary conditions.

During 2017, to address the Tribe's interests as expressed during the Kick-Off meeting and later conversations, the ETG team worked primarily on Task 3 ("Assessment of the Klamath Estuary Spit"). In January 2017, the Tribe's Project Manager (Sarah Beesley) approved the addition of Task 10 ("Mouth Closure Analysis") at no additional cost to the Tribe, to support the spit assessment. The results of the mouth closure analysis are incorporated into this Task 3 report.

The spit assessment and mouth closure analysis described in this document are limited by the available data. The ETG team's first step in the assessment was to work with Yurok Tribe staff to collate the Tribe's monitoring data needed for the mouth closure analysis -- particularly photographic records of the estuary mouth, and measured water surface elevations. In addition to these data from the Tribe, other primary "drivers" or controlling factors considered in this analysis were wave energy and river discharge. These drivers' effects on mouth configuration were analyzed for the events identified in the photographic records and in the Tribe's water surface elevation data for the estuary, and a "closure index" was calculated using these data. As described below, available data did not cover a long period of time, and even within recent years, the water level record was incomplete for some periods, preventing calculation of the mouth closure index.

This spit assessment does not analyze how climate change might affect future berm dynamics or resulting water levels. Climate change may affect the complex relationships between the physical drivers that control estuary mouth configuration. However, due to limited available data and the scope of this project, we had to assume that the current relationships between sea level, wave conditions, and berm height would remain applicable under climate change conditions. Thus, the water levels projected (and mapped in Appendix 2) consist simply of sea level rise increments added on top of current perched water levels.

This study's analysis, and its mapping of potential inundation, do not account for hydrodynamics, large river flood events, potential future dam removal, or other factors beyond the methods described. Topography, large river floods, and flow barriers (e.g. filled lands, dikes, berms, restrictive culverts, and water control structures) obviously affect estuary water levels and inundation of nearby land surfaces. Dam removals may affect estuary bathymetry and floodplain topography via changes to sediment deposition and erosion patterns. Large river floods have radically changed the estuary's topography in the past. However, the scope of this study did not include a hydrodynamic model, sediment modeling, or studies of erosion/deposition caused by flooding, so changes to water levels due to these factors were not considered. Instead, the potential inundation map in Appendix 2 was built using a "bathtub model." The map, and this study's results, must be used with these limitations in mind.

This report completes the ETG team's assessment of the Klamath estuary spit, and thus completes Task 3. Next steps for this contract include working with the Tribe to incorporate this information into their climate change adaptation planning for the estuary.

Historical evolution of the Klamath River mouth (spit, mouth, and shoals)

The evolution of the mouth has been documented in surveys from the mid-18th century onwards and more recently by aerial photographs from the 1950s (Hiner and Brown 2004, Laird 2008). The surveys show the spit and mouth to be in various locations. It is important to note that these surveys are snapshots in time, and the mouth would have been moving, opening, perching, and closing more frequently than indicated by these snapshots, as it does today. More significant from these surveys are the long-term evolution of the estuary and shoals behind the spit. From the 1870s to the 1920s, three vegetated islands were also consistently present in the estuary during this period, as can be seen in the 1915 survey below (Figure 1).

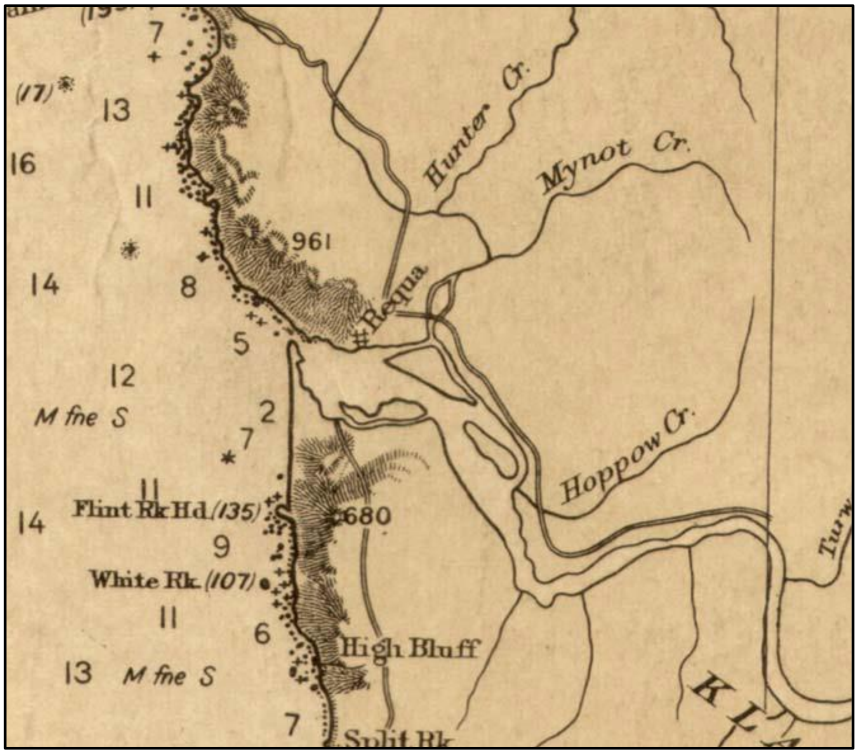


Figure 1. 1915 survey of Klamath River estuary showing a typical configuration in early 20th century surveys (Laird 2008).

Between 1921 and 1927 there was a coalescing of the most westward island to form the land surrounding South Slough (Figure 2).

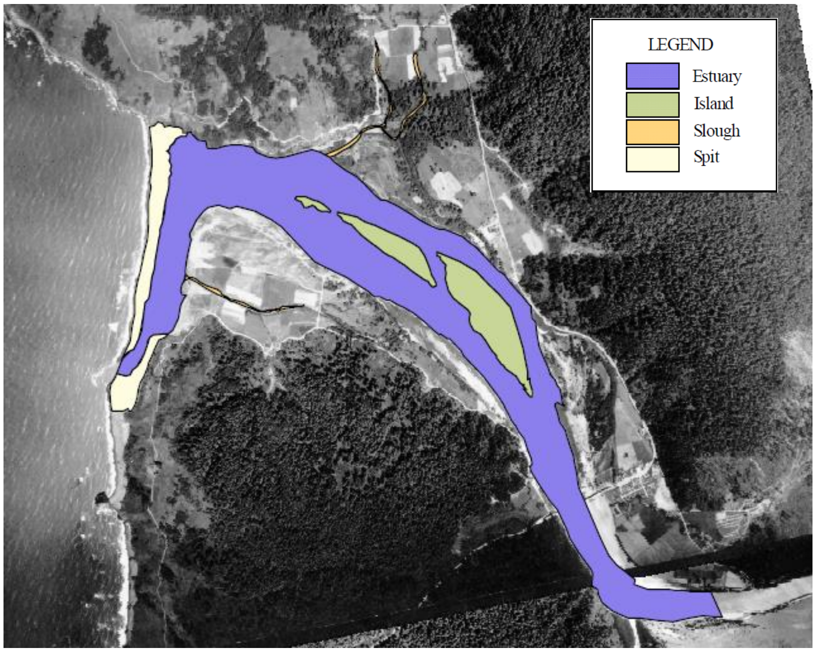


Figure 2. 1936 aerial photograph of Klamath River estuary (Hiner and Brown 2004)

By the late 1940s, there was the further creation of shoals in the mainstem that coalesced with the south bank; distributary channels that formed on the south bank gradually filled in creating backwater slough habitat. Closure of the distributary channels resulted in more flow in the main stem to the north.

Photographs and publications describe a large river flood event in January 1953, with peak flows estimated at more than 6500 m^3/s (>230,000 CFS) at Klamath (Rantz 1959). This event was sufficient to reactivate the distributary channels through the South Slough. Flow was re-established on the south side of the mid-channel shoals, with complex braiding and mature vegetation on the islands (Figure 3). There also appears to have been a significant scouring of the Hunter Creek/Salt Creek mouth on the north bank. The 1915 survey shows Salt Creek merging with Hunter Creek, and then flowing as a single stream into the Klamath. Later maps show Salt Creek with its own mouth west of Hunter Creek.

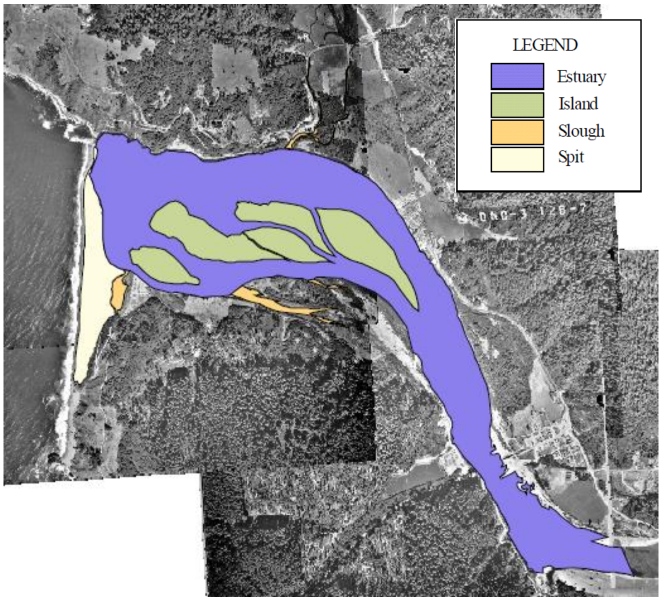


Figure 3. 1963 aerial photograph of Klamath River estuary (Hiner and Brown 2004)

There was further change by the early 1960’s following significant flooding in 1955. Mid-channel islands were more prevalent than before, with extensive channel braiding between them, including regions of the south slough. The South Slough region was much wider than in 1954 and appears to have continuous freshwater flow through it. Scouring of the Hunter Creek/Salt Creek mouth continued.

Following another flood in 1963, sediment deposition was widespread throughout the south slough region; the islands present in 1969 are one continuous unit with several main slough channels extending westward toward the estuary’s lower embayment (Figure 4).

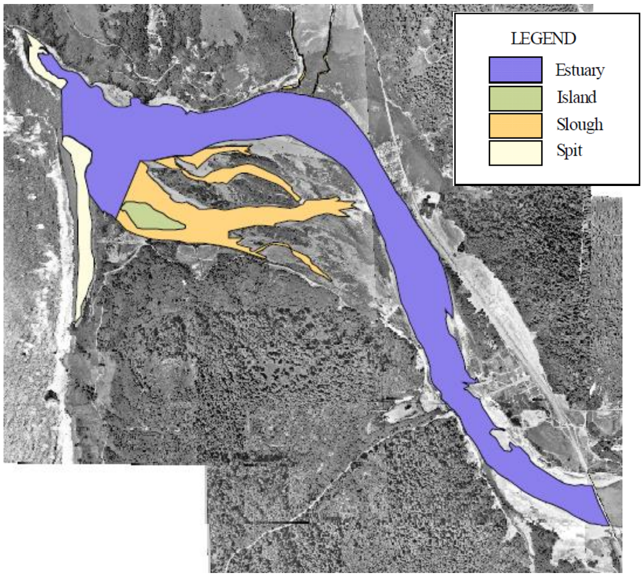
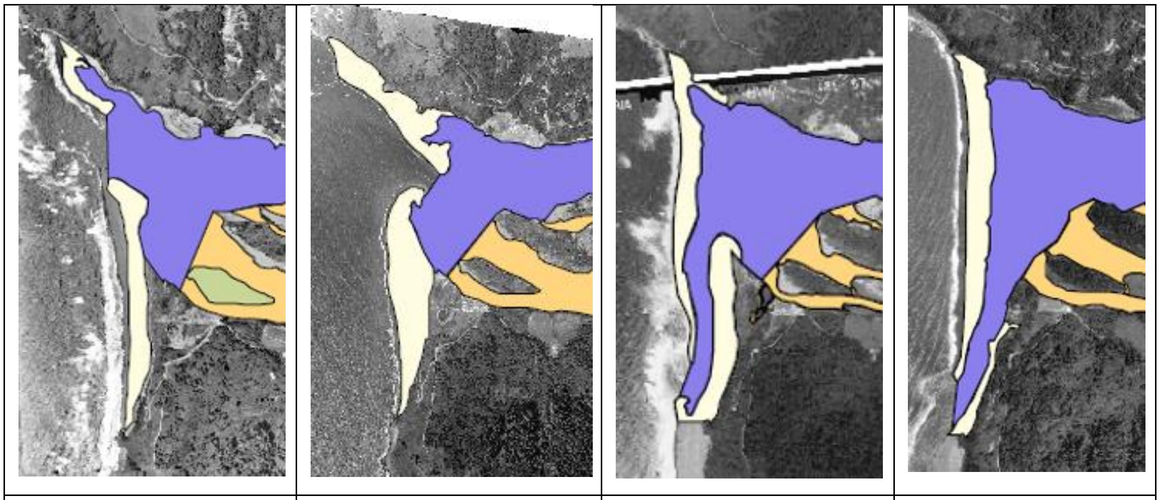


Figure 4. 1969 aerial photograph of Klamath River estuary (Hiner and Brown 2004)

The configuration of islands within the lower estuary has remained essentially the same since the 1970's. The snapshots of the 1970's to 90s show the mouth in various position (Figure 5). In the 1972 image, the mouth was in the middle of the channel, with a small embayment on the north side between the spit and Oregos. In the 1985 and 1993 images, the mouth is shown to have migrated to the south end of the estuary via a long chute that originates near the middle of the channel and runs diagonally to the south between two sand spits. As mentioned above, these types of mouth configuration changes occur frequently even within a single year (see "Identification of mouth opening, closing and perching events" below).

None of the surveys or photographs show the mouth to be completely closed. The mouth is often shown as being constricted, with a hairpin turn in the channel as it crosses the bar. These images suggest that constriction (perching) often occurred in August-September.



1969	1972	1985	1993

Figure 5. Mouth position 1972, 1985, 1993 (Hiner and Brown 2004); see legend on Figures 2-4.

Conceptual model of mouth evolution

Mouth morphology in the Klamath River Estuary is governed by a balance between wave-driven sediment transport and river flow, augmented by the ebb tidal flow (Behrens et al., 2015). The interaction of these forces and their effect on mouth closure and opening are illustrated in Figure 6. The red ellipse shows the wave processes that try to close the mouth; the blue ellipse shows the river processes that try to keep the mouth open. Intermediate conditions occur where the estuary's connection to the ocean is constrained by the presence of a berm and the mouth is “perched.”

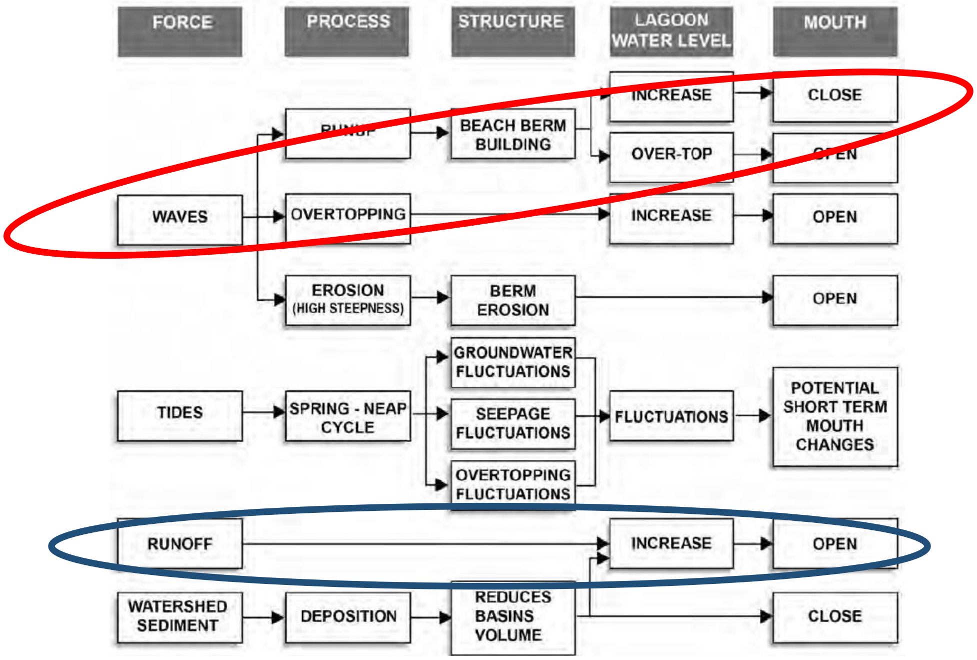


Figure 6. The dominant physical forces and their influence on water level and mouth closure (from Behrens et al. 2015).

The primary cause of **mouth closure** is the development of a high beach berm across the mouth of the estuary during periods of high wave energy. **Mouth opening** is primarily driven by the water levels inside the estuary that, if sufficiently high, lead to overflowing of the berm and the cutting of a channel, allowing reconnection to the ocean (Figure 7). The open and closed state are two bookends of a continuum. Intermediate conditions occur when the connection to the ocean is constrained by the presence of a berm. This intermediate condition is referred to as a "**perched mouth"** (Figure 7), and it is characterized by a high beach berm; elevated water levels within the estuary relative to the ocean; damping of tidal fluctuations; and a reduced outflow of water and nutrients from the estuary compared to the open condition. In the perched condition the wave-driven transport and river flow shown in Figure 7 are balanced.

Figure 7a. September-October 2007 showing the mouth perched (left) and open (right)

Figure 7b. November 2011 showing the mouth perched (left) and open (right)

During perching and closure, river flows are impounded, often resulting in elevated water levels inside the system. For the Klamath, water levels within the estuary when it is closed are affected by inflow from the Klamath River; by runoff from the immediate watershed; by waves and extreme high tides that overtop the berm; by tides which affect groundwater elevations; and by seepage through the berm. All of these events are likely to increase water levels within the estuary and increase the likelihood of opening. These events will also increase the likelihood and duration of the mouth staying open. Another controlling factor, tidal prism, similarly affects estuarine water levels and the likelihood and duration of mouth opening. Tidal prism is a measure of the amount of water entering the estuary on each tide when it is connected to the ocean; a decrease in the tidal prism due to sedimentation will make the mouth more susceptible to closure in the next high wave event.

Many river systems show similar patterns of perching and closure. The frequency and duration of berm closure of these systems – and the resulting impoundment - vary along a continuum between open rivers, which never form a berm, and true lagoons, which do not have a strong river influence and are commonly isolated from oceanic tidal exchange for long periods. **However, all of these systems share a common pattern: river mouths that are closed tend to**

stay closed until there is a significant river event, and mouths that are open tend to stay open until there is a significant wave event (McSweeney et al 2017).

In a large watershed like the Klamath, the river influence can be much larger than the tidal prism, due to runoff from the watershed. Thus, the Klamath seldom closes completely, and when it does, the closure is generally brief. However, the estuary frequently shows bar formation and perching of the mouth due to wave action.

In the Klamath and similar systems, forcing by waves and by river events - and resulting mouth closure or perching - has a significant seasonal (annual) component. However, there are also significant temporal cycles affecting mouth closure or perching that are not annual. These vary from system to system. Behrens et al. (2015) suggest three temporal scales for mouth dynamics, based on their observations of the Russian River, with different factors controlling closure:

> Tidal scale: closure is the result of an imbalance between short-term wave-driven sediment import and export from the scouring flows through the mouth resulting from tides and river flow. The factors for closure at the neap/spring tidal scale tend to be the hydraulic characteristics, such as the mouth flow rate, the mouth width to depth ratio, and the tidal prism.
>
> Seasonal scale: at this scale, the closure pattern may be controlled by interactions between seasonal cycles in wave height and river flow. Here the controlling factors may be more closely related to wave-driven longshore sand transport, which is the dominant contributor of sediment during closures. When combined with strong seasonal winds and waves, reduction of river flows in summer and fall may allow partial or complete closure of the mouth; while increased river flows in late fall and winter may keep the mouth open despite strong winter winds and waves.
>
> Multi-year scale: closure may be related to the year-to-year variation in river flow. For example, in the Russian River, there has been a shift from lengthy, dry-season closure events to relatively short (less than two weeks) events concentrated in the fall and spring seasons (Behrens et al. 2015). Also, changes in the peak flows caused by the construction of dams may also be responsible for changes in the timing and likelihood of closure.

In brief, mouth closure is most likely with relatively high waves during times of low river discharge; and mouth closure may be more likely on neap rather than spring tides.

Mouth closure model

A mouth closure index or stability index (S) can be formulated to illustrate the likelihood of mouth closure as the ratio between wave power (P_w) and combined river flow and tidal power (P_t) (Williams and Cuffe, 1994):

$$S = P_w / P_t \,, \qquad P_w = 0.5 \rho g H_s{}^2 C \,, \qquad P_t = \frac{\gamma h_T}{b} \left(\frac{\Omega}{T} + Q \right)$$

where P_w is the offshore wave power, H_s is significant wave height, C is wave group velocity, P_t is the tidal power enhanced by an additional outflow due to river discharge, h_T is the tidal range, b is the mouth width, Ω is the tidal prism, T is the ebb tide period, and Q is the river discharge. P_w will be higher for larger offshore waves. P_t will be higher for larger tidal prisms, higher river discharge, higher precipitation, and smaller breaches. The value of S is generally below 5 for open systems; values above 10 indicate increased likelihood of closure (Williams and Cuffe, 1994). In the Pacific Northwest, high winter precipitation and resulting high winter river discharge would tend to create a larger value of P_t, which would reduce the value of S in winter. Therefore, closures would be more likely in summer or fall, when river flows are lowest.

Using the formulas above, an "closure index" can be calculated on a daily basis from wave, tidal and streamflow data (Figure 8).

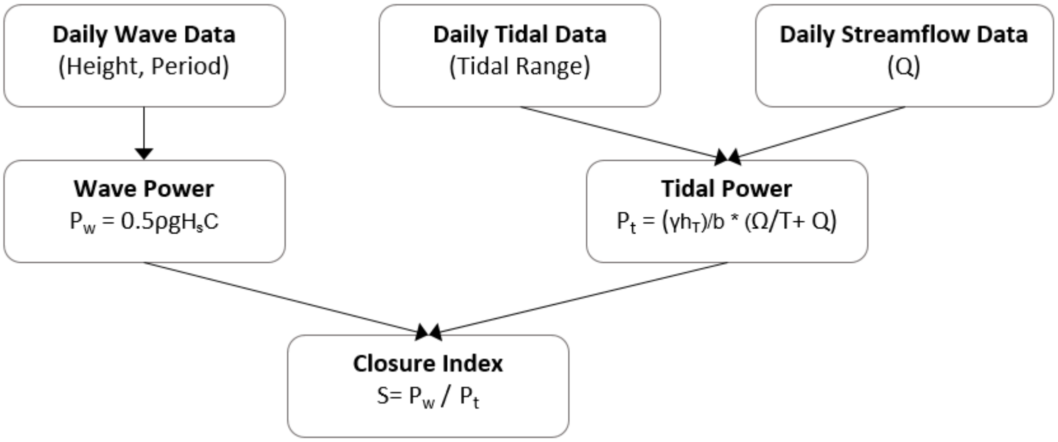


Figure 8. Calculation of daily closure risk

Identification of mouth opening, perching and closing events

To apply the principles above to the Klamath River spit, we needed to identify specific times when mouth configuration changes occurred (that is, mouth opening, closing, and perching events), in order to correlate those changes to the levels of the drivers in Figure 8 above. To identify these events, we contacted the Yurok Tribe and requested their photographs of the estuary mouth. The Tribe provided a time series of oblique mouth photographs from 2007 to 2017. We collated those photographs to identify a series of events during which the mouth changed its configuration, resulting in either opening, closure, or perching.

We used the hydrologic time series (waves, river discharge, and estuary water surface elevations) to quantify the drivers of the mouth closure index, P_w and P_t. Wave power data were obtained from NOAA's Cape Mendocino buoy, as it had a longer continuous time series than the closer Humboldt Bay buoy. Klamath River discharge data was obtained from USGS gauge 11530500 near Klamath. Water surface elevations were provided by the Yurok Tribe, measured at the Requa boat launch gauge. Tidal datums were also provided by the Yurok Tribe;

these were calculated by JOA Surveys from the Tribe's Requa gauge data (Table 1). All elevation time series and tidal datums were corrected to a common elevation datum (NAVD88).

Table 1. Tidal datums at Requa boat launch gauge

Datum	Elevation (m NAVD88)
MHHW	2.23
MHW	2.06
DTL	1.47
MTL	1.48
MSL	1.45
MLW	0.91
MLLW	0.70

We compared the time series of drivers with the photographic record of events at the mouth. The following are example events; other events are described in Appendix 1.

Mouth opening event of January 2012 (Figure 9)

This event is identified as event 8 in Table 2 and Appendix 1. In this event, the mouth was perched up to January 20, during a period of low river flow and relatively high wave energy, which caused the closure index to peak. The water levels gradually increased from 2 m to 4 m as water backed up in the estuary behind the berm. The opening of the mouth appeared to be correlated with an increase in river flow, which widened and deepened the mouth, re-establishing oceanic tides within the estuary as can be seen in the water surface elevation record. At the same time, the closure index approached zero, indicating the dominance of the flow energy over the wave energy.

Mouth perching event of October 2012 (Figure 10)

This event is identified as event 9 in Table 2 and Appendix 1. In this event, the mouth was open up to October 20, during a period of relatively constant river flow. Starting on October 14, wave energy increased and peaked about October 17. The combination of low river flow and high wave energy caused the closure index to spike on October 22 and peak October 24. Water levels, which had been fully tidal up to October 20, were increasingly damped, presumably as the beach berm built up due to the wave action. By October 23 the berm had built up sufficiently for the oceanic tide to be cut off completely, and water surface elevation was then governed by river inflow. The perching of the mouth appeared to be correlated to low river flow and increasing wave energy, which built up a berm, pushed the channel into a hairpin form and shallowed the mouth.

01/17/2012 01/20/2012

Figure 9. Mouth opening event of January 2012 – vertical lines indicate dates of photographs

10/09/2012

10/23/2012

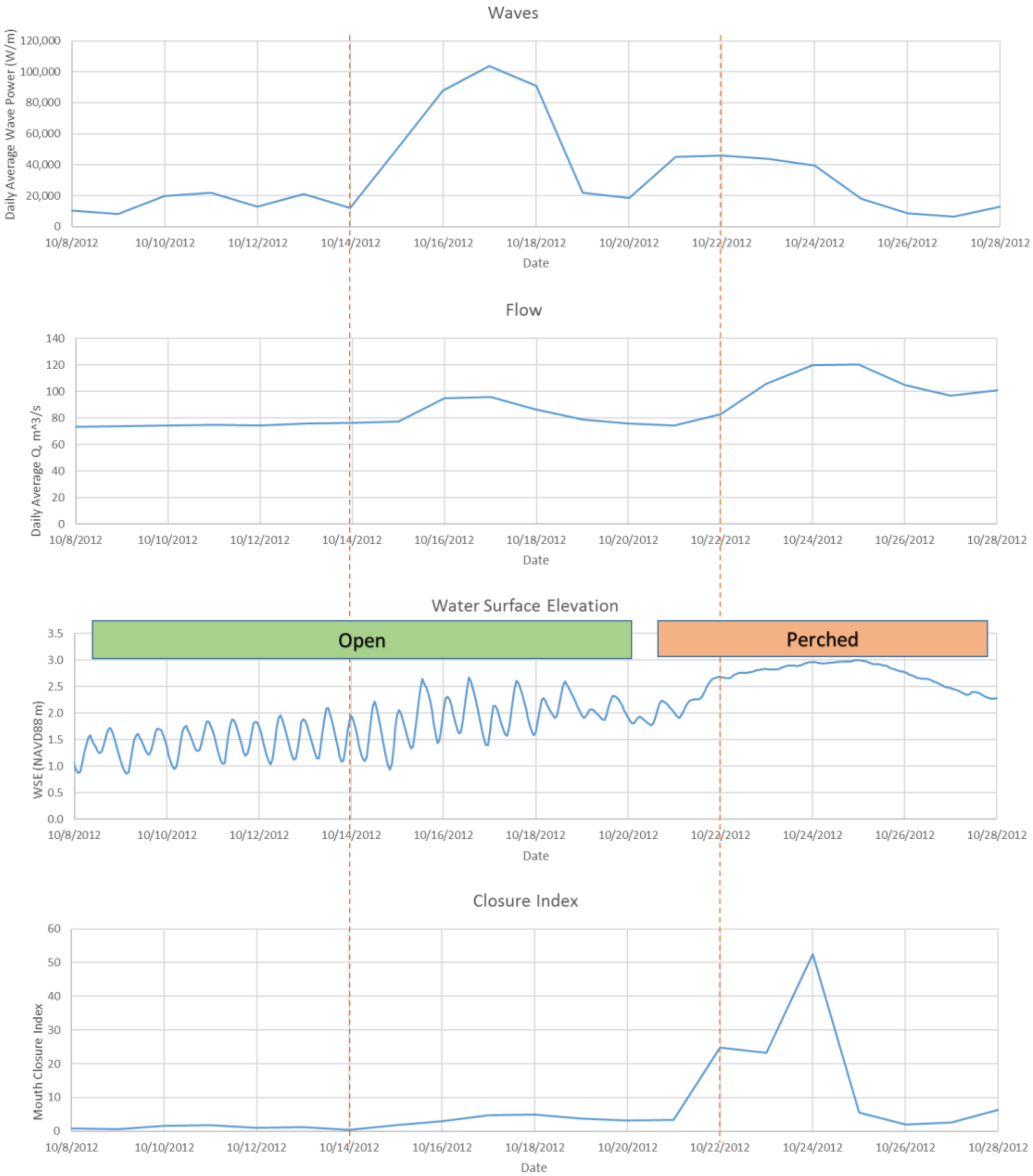


Figure 10. Mouth perching event of October 2012 – vertical lines indicate dates of photographs

Summary of mouth opening, perching, and closure events

Table 2 summarizes the 14 opening, perching, and closing events observed in the photographic record obtained from the Yurok Tribe. These events are detailed in Appendix 1. For each event, the table shows peak flow discharge, maximum unit wave power, peak water surface elevation (WSE), and peak closure index (NOTE: see next page for details regarding peak values). The deliberate opening event (Figure 12) is omitted from this table because it was controlled by human activity, not hydraulics.

Table 2. Summary of mouth opening, perching and closure events

Event	Event Type*	Start	End	Peak Discharge (m^3/s)	<- date	Max Wave Power (kW/m)	<- date	Peak WSE (m NAVD88)	<- date	Peak Closure Index	<- date
1	Opening	2007-09-25	2007-10-03	95	03-Oct	94	02-Oct	2.6	9/25-9/27	NO DATA	
2	Opening	2008-12-09	2009-02-27	1634	24-Feb	369	07-Feb	3.6	23-Feb	4.0	15-Feb
3	Perching and re-opening	2009-10-12	2009-10-19	225	15-Oct	205	14-Oct	2.9	5-Oct	NO DATA	
4	Opening	2010-10-18	2010-10-27	725	25-Oct	424	25-Oct	NO DATA		NO DATA	
5	Perching	2011-08-23	2011-11-08	222	11-Oct	223	1-Nov	NO DATA		NO DATA	
6	Opening	2011-11-22	2011-11-29	456	24-Nov	304	19-Nov	NO DATA		NO DATA	
7	Opening	2011-12-18	2011-12-27	123	roughly constant	182	09-Dec	NO DATA		NO DATA	
8	Opening	2012-01-17	2012-01-20	2540	21-Jan	187	19-Jan	3.9	19-Jan	31.8	16-Jan
9	Perching	2012-10-16	2012-10-23	120	24-Oct	104	17-Oct	3.0	25-Oct	52.5	24-Oct
10	Opening	2012-10-30	2012-11-13	167	2-Nov	169	9-Nov	2.9	1-Nov	12.6	10-Nov
10a	Perching and re-opening	2013-08-07	2013-10-16	596	30-Sep	419	30-Sep	5.0	30-Sep	89.2	8-Sep
11	Perching and re-opening	2013-11-05	2014-01-07	194	20-Nov	240	19-Dec	5.3	31-Dec	190.5	19-Dec
12	Perching and re-opening	2016-09-30	2016-10-16	784	17-Oct	273	15-Oct	4.1	14-Oct	11.1	12-Oct
13	Perching and re-opening	2017-02-11	2017-03-05	6456	10-Feb	265	16-Feb	4.5	10-Feb	0.8	20-Jan

* See next paragraph for discussion of "Event Type"

The "Event Type" in Table 2 above reflects one or two predominant features of the morphological behavior observed in the photo record, and the start and end dates reflect the dates the defining photographs were taken. However, in reality, every perch or closure is associated with an opening event, and vice versa. Additionally, the interplay of the controlling factors (Figure 8) is complex and fluid, resulting in a continuum of event magnitudes. Due to this continuum of morphological behavior (both in time and magnitude), it is difficult to assign a maximum value for parameters such as water surface elevation, since these parameters vary in complex ways during different parts of the event. Therefore, maximum values given in Table 2 were sometimes selected to coincide with the described event type, providing a more useful comparison than an absolute maximum. Thus, the maximum shown in Table 2 may be different from the absolute maximum for the entire time period – or may even have occurred slightly outside of the time period shown in Table 2. To view relationships between controlling factors in detail, see the charts in Appendix 1.

The event time series in Table 2 shows that perching in a hairpin channel or chute across the berm is a common morphological behavior. It appears that wave energy is sufficient to cause littoral drift along the spit in most conditions, and that wave energy is continually trying to form a berm. For most of the events, the berm is relatively high, a hairpin or chute channel is formed, and the mouth is “perched.” At the same time, there is continual river flow that prevents the mouth from closing completely for any substantial length of time. It appears that the closure index can be relatively high, but the mouth can remain open, depending upon the magnitude of river flow.

Opening of the estuary mouth is associated either with development of a critically high water level (e.g. >5 m, as in event 11), or the development of a moderately high water level coupled with an average daily flow greater than ~ 170-200 m^3/s (as in events 8, 10, 10a, and 12). In addition, as shown during events 8, 10, 10a and 12, wave power, the rate of change in discharge, and the timing of the increased discharge relative to changes in wave power appear to be important in controlling opening of the mouth. Ocean tide level at the time of breaching may play a role as well, with low tides contributing to opening by increasing erosion potential at the mouth, and high tides having the opposite effect.

At higher river flows (as in events 2 and 13), sudden dramatic increases in flow can cause a perched condition that transitions rapidly to an open one. This may be due to a temporary back-up of water that persists until the mouth is eroded sufficiently to convey the suddenly increased discharge.

We reviewed the water level data associated with the events in Table 2 to locate the highest values, and to determine their context relative to mouth configuration. Of the water levels that could be validated and adjusted to the common elevation datum, the two highest observed values were the peaks associated with events 10a and 11, both of which occurred when river flow was low. The perched conditions associated with the high-discharge events 2 and 13 caused high water as well, but only for a period of a few days; while the high water levels associated with low-flow perched conditions persisted for weeks or even months. This indicates that seasonality of mouth closure is a major controlling factor in both maximum water surface elevation and maximum duration of inundation in the estuary.

The key findings from the events identified in the records described above (through June 2017) were:

- Perching seems to be a common condition; it occurs when the mouth is neither fully closed or fully open. Perching seems to occur when two conditions are present:
    - River flows are below 200 m^3/s.
    - There is sufficient wave energy for the mouth closure index to be above 50.
- The mouth seems to remain perched until one of the following occurs:
    - A critically high water surface elevation develops in the estuary (>5m NAVD88), or
    - The daily averaged river flows increase to exceed 170-200 m^3/s at the USGS gauge 11530500 near Klamath. The rate of the increase in flow and its timing with respect to wave power may be more important than the actual magnitude of flow.
- Complete closure of the mouth is rare and short-lived.
- Perching during low river flow is associated with the highest water levels and the longest duration of high water levels.

Significance of opening and perching events, and management intervention

The potential significance of mouth opening and perching events to the ecological health of the estuary is well-illustrated by a longer time series from August 2013. During this period, the mouth was perched and estuary water levels were relatively high, much higher than the oceanic water levels. This time series shows both the perching of the mouth and the subsequent opening.

Mouth perching and opening event of July to October 2013 (Figure 11)

This event is identified as event 10a in Table 2 and Appendix 1. The water surface elevation record showed a tidal signal at the end of July, which was gradually damped as waves build up a berm. By the end of July, only the peak of the high tide was seen within the estuary. By August 22, there was no tidal action within the estuary, and the water surface elevation was governed by river inflow and outflow over the berm to the ocean. Water levels remained high at about 3m NAVD, higher than oceanic tide levels, throughout September. Peak water level within the estuary was about 5 m NAVD88, around September 30. This period corresponded to a peak in wave energy, which built up the berm above normal levels. It also coincided with a peak in the river inflow of about 600 m^3/s. This peak flow appears to have been sufficient to erode the berm built up by the waves, allowing the lowering of the estuary water levels, and allowing oceanic tides to re-establish within the estuary. This pattern of perching and opening was reflected in the closure index. It is notable that the closure index shows some peaks through July, August, and September above 30, indicating berm buildup and river flow insufficient to erode the channel. About September 30, the closure index falls away rapidly below 10 at the same time as a peak occurs in the river inflow. (This event was not detected in the initial photo analysis but was added later following information provided by the Yurok Tribe.)

08/07/2013 10/16/2013

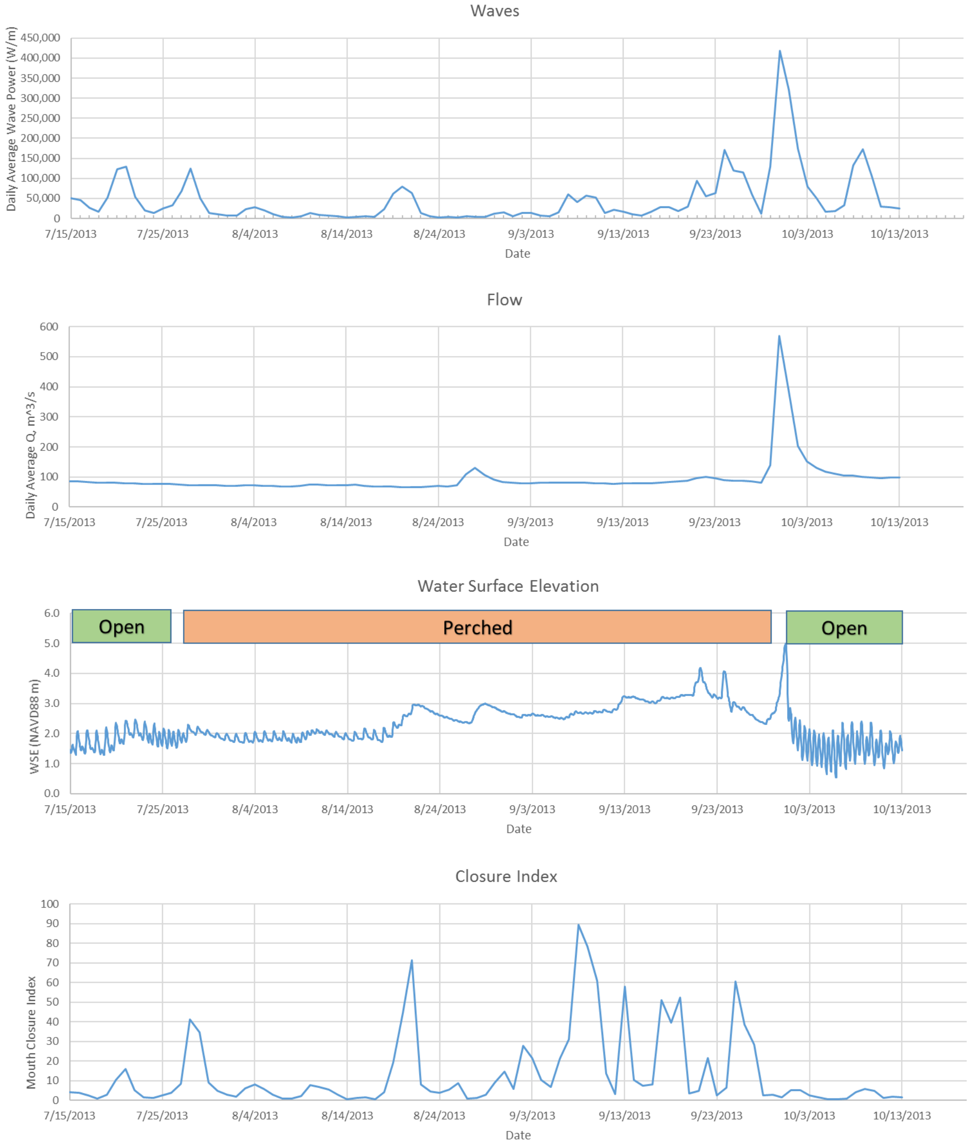


Figure 11. Mouth perching and opening event of July to October 2013

Deliberate mouth opening event of August 2015 (Figure 12)

Not all mouth opening events were due to river inflow events. In August 2015, following a prolonged period of closure, tribal members deliberately breached the beach berm (personal communication, Sarah Beesley). In this event, the berm was breached on August 19; the estuary water level dropped immediately. Before breaching, only the very top of the tide can be seen within the estuary; after breaching, the full tidal range was re-established. Before breaching, the closure index was above 30 on some occasions, which suggests that the berm was continuing to build and would have remained closed without intervention. The river inflow was relatively low during the whole period with a small peak coincident with the breaching. Towards the end of the period, about September 10, the oceanic tide signal diminishes, and the berm appears to build up again.

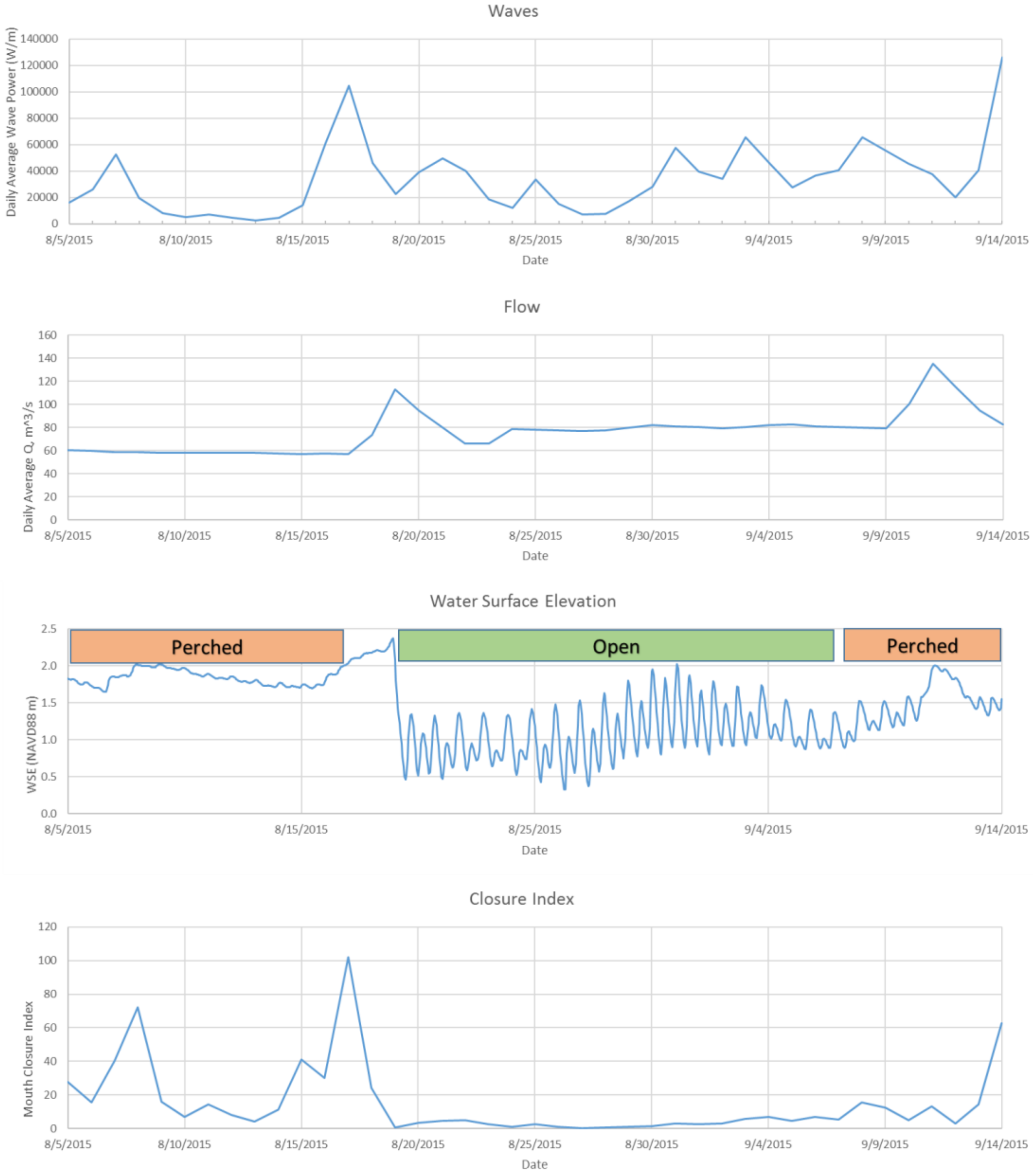


Figure 12. Deliberate mouth opening event of August 2015

Impacts of mouth configuration state

Water levels when mouth is open, perched, or closed

Inflows of water to the estuary include Klamath River discharge, direct precipitation onto the estuary surface, runoff from the surrounding local watershed, groundwater seepage, and tidal inflow during periods when the mouth is open. The outflow of water from the estuary is predominantly due to the opening of the mouth and evapotranspiration losses, particularly during the summer months. The water balance for a specified period can be written as

water inflow – water outflow = change in water storage

Changes in the balance reflect changes in the volume of water stored in the estuary and hence the elevation of the estuary; the actual change in estuary water surface elevation is a function of the change in water storage and the bathymetry of the estuary.

To determine the effect of mouth opening, perching and closure on the estuary water surface elevation, these factors must be considered:

1. the timing of mouth opening, perching and closure;
2. the date and estuarine water level at perching or closure; and,
3. the river discharge and precipitation following the perching or closure.

The degree of closure of the mouth (the amount of perching) depends on the height of the berm, which in turn is a function of both the high tide elevation (MHW) and the significant wave height (H_s) (Behrens et al. 2015):

$$h_{berm} = MHW + H_s$$

If the estuary water surface elevation is less than h_{berm} then the mouth remains closed. If the estuary water surface elevation is greater than h_{berm} then there will be outflow and, if the river flow is large enough, erosion of the berm will lead to the opening of the mouth.

When the mouth is open and the channel is straight following a high river flow, the water surface elevation measured within the estuary shows a strong tidal signal. The tidal signal is a result of the deepening of the mouth channel during high river flow, which allows the augmentation of the river flow with a large tidal prism. The hydraulic energy of the increased tidal exchange helps keep the mouth open longer but is probably not a major factor in opening the mouth. However, as noted in "Summary of mouth opening, perching, and closing events" above, timing of changes in river flow and wave power relative to tide cycles can affect the likelihood of mouth opening.

We had limited closure events in the photo record. The most common event was perching, and the timing of the perching was important in setting the new muted tidal or non-tidal water surface elevation in the estuary.

The time series for water surface elevation for a perched mouth shows two characteristics. First, high tide under perched conditions can sometimes be seen as a small peak or “blip” in the water surface elevation record - as opposed to a full tidal cycle visible during open, non-perched conditions. Second, depending on river discharge, there tends to be a gradual increase in water surface elevation over time, corresponding to buildup of river inflow. Tidal cycles in water level become muted or absent as this gradual buildup proceeds. Under these conditions, water surface elevations can exceed typical high tide elevations.

Within the events we analyzed, the typical maximum water level observed during perching and closure events was around 2.5 m above MHHW, or 4.7 m NAVD88. We refer to this typical water surface elevation during perching as "Highest Observed Water Level (perched)" or "HOWL (perched)." The maximum observed water surface elevation in the time series was 5.3 m NAVD88 (about 3.1 m above MHHW), just prior to the mouth opening in event 11.

Climate change effects on mouth configuration and water levels

If the mouth is perched, then the maximum water surface elevation inside the estuary could be as high as 2.5 m above MHHW depending on the river discharge and the elevation of the berm, as described above. With additional local data (local wave gauge, longer time series, etc. – discussed in "Data recommendations" below) it might be possible to develop a statistically predictive, calibrated closure index. This index could be used to estimate future mouth perching or closure events (and their frequency and duration), using a daily time series of predicted wave heights, water levels, evaporation rates, and river discharges. For each time increment, the mouth closure index (S) could be calculated to determine the risk of perching or closure. The predicted water level in the estuary could then be computed as a future time series. This calculation chain is shown in Figure 13 below.

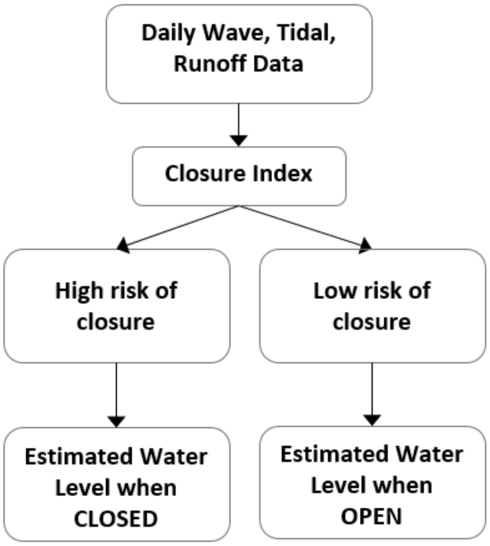


Figure 13. Calculation chain for using closure index to estimate estuary water levels

If local wave data were available, these calculations could be made with daily time series of projected wave heights, water levels, evaporation rates, and river discharges for 2050 and 2100 to estimate likely climate change effects on mouth closure frequency and duration. However, given the uncertainty in how these factors may be affected by climate change, the simplest assumption is to assume that the frequency and magnitude of the river discharge, and hence the frequency of opening and closing, will remain similar; and therefore, the only change will be an increase in high water elevation as sea level rises. In this case, the height of the berm and the maximum water surface elevation become:

$$h_{berm} = MHW + H_s + SLR$$

In other words, the assumption is that the berm will continue to build its elevation to match the rising sea level.

Therefore, until there are local wave data to estimate berm height (or direct measurements of berm height), the simplest way to estimate the effect of climate change on water surface elevations in the estuary is to add projected sea level rise to the observed maximum water elevations (HOWL - perched).

We determined potential water surface elevations for perched conditions in the estuary under sea level rise scenarios using this principle. As described above, the typical Highest Observed Water Level (HOWL) during perched conditions was 2.5 m above MHHW. To obtain future elevations of HOWL (perched) under sea level rise scenarios, we simply added sea level rise increments from recent publications to the current value of HOWL (perched). Projections of future sea level rise for Crescent City have recently been published (Griggs et al. 2017). The range of projections for 2050 and 2100 for the RCP 8.5 scenario were used to estimate a range of future maximum water surface elevations for HOWL (perched) (Table 3). The RCP 8.5 projections assume that emissions continue at about the present rate; if this is the case, the projections have a 67% probability of occurring (Griggs et al 2017).

Table 3. Representative values for the elevation of "Highest Observed Water Level" ("HOWL") during typical perching events in the estuary, with sea level rise increments added from Griggs (2017).

Year	Sea level rise (m)	HOWL (perched) (m NAVD88)
Current	n/a	4.7
2050	0.06-0.21	4.8-4.9
2100	0.21-0.76	4.9-5.5
2150	0.40-1.34	5.1-6.0

Mapping potential inundation (current, and under sea level rise scenarios)

We mapped potential inundation from the scenarios and water levels shown in Table 3, plus two additional scenarios, one on the low end (current MHHW, 2.2 m NAVD88) and one on the high end (the "high" scenario of NOAA 2017). Table 4 shows the mapped scenarios and water levels and their derivations; the potential inundation map is provided in Appendix 2.

Table 4. Water surface elevations (WSEs) mapped in Appendix 2, and their sources.

WSE (m NAVD88)	Year	Datum	Sea level rise (m)	SLR source
2.2	Current	MHHW	None	n/a
3.0	2100	MHHW	0.8	RCP8.5, Griggs 2017
4.7	Current	HOWL, perched	None	n/a
5.5	2100	HOWL, perched	0.8	RCP8.5, Griggs 2017
6.7	2100	HOWL, perched	2.0	"high" SLR scenario, NOAA 2017

The potential inundation mapping in Appendix 2 does not account for flow barriers such as levees, tide gates, restrictive culverts, filled areas, or road embankments. Such barriers affect the actual extent of inundation; see "Impacts of mouth perching and closure" and "Opportunities for further investigation" below for further discussion.

Impacts of mouth perching or closure

The consequences of mouth perching or closure can be significant. Complete closure eliminates water exchange with the ocean and significantly increases the retention time of water in the estuary. A perched or constricted mouth may have a connection to the ocean, but oceanic exchange is still reduced. In intermittently closed or intermittently open estuaries in general, the ecological impacts of mouth state are mediated by many other factors such as dam operations, levees and other flow barriers, and nutrient loading (Figure 14).

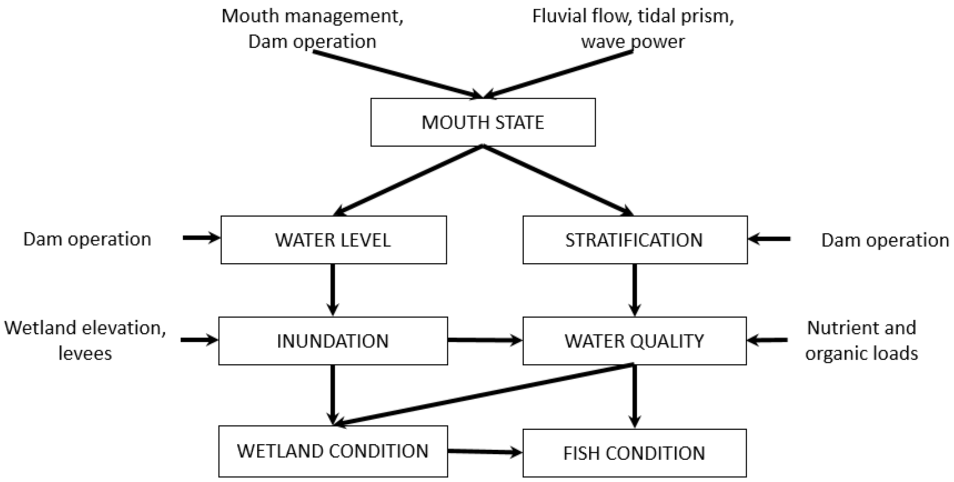


Figure 14. Influence of mouth state on estuarine conditions (after Largier, 2016)

As shown in Figure 14, perching and closure have the potential to affect ecosystems of the Klamath estuary, particularly wetlands, floodplains, and riparian areas. Examples of the physical conditions affected by perching and closure include water levels (and associated inundation); water quality parameters such as temperature, salinity, dissolved oxygen; groundwater level; and groundwater salinity. All of these physical conditions are controlling factors or "ecosystem drivers" for wetland, floodplain and riparian ecosystems – in other words, they are very important to ecosystem functions.

Since the drivers of mouth configuration are the estuary's natural forces of river discharge, wind and wave power, and tides, it is reasonable to assume that ecosystems of the Klamath estuary evolved under conditions of a dynamic river mouth, with perching, closure and open conditions occurring in response to these natural forces. The high water levels associated with perching – which greatly exceed estuarine high tides -- have historically inundated nearby wetlands and floodplains. These inundation events have likely been important in structuring the plant and animal communities that formed in and around the estuary, and in setting the stage for valued ecosystem services and functions. Examples of wetland functions supported by inundation during perching include fish and wildlife habitat, nutrient processing, food web support, and water temperature moderation.

Potential water quality impacts of perching include changes to salinity, temperature, and stratification. While the perched arrangement of the mouth is not necessarily a physical barrier to fish (they have been observed swimming in and out of the mouth when it is perched), perching may cause water chemistry changes that could present physiological barriers to fish use. For example, a decrease in estuarine salinity during perched conditions could affect juvenile salmon's ability to adjust to salinity prior to ocean entry. Changes to salinity or water temperatures could also contribute to development and spread of diseases among fish using the estuary. On the other hand, the high water conditions associated with perching could also allow access to foraging habitats typically not available to fish and other aquatic organisms; and these high water conditions also support the wetland functions listed above (such as water temperature moderation, nutrient processing, and food web support), which benefit fish and other aquatic organisms.

As shown in Figure 14, structures such as dams and levees mediate the effects of mouth state on ecosystems. After European settlement of the Klamath estuary area, flow barriers (such as dikes, levees, and filled areas) and flow diversions (such as ditches and culverts) were constructed to facilitate human activities like agriculture and to protect infrastructure like homes and businesses. These flow barriers and diversions have altered the area inundated during perching events. Drained and hydrologically-disconnected wetlands often have reduced ecosystem functions and may no longer support the native species that were originally found in these habitats prior to alteration. Further, flow barriers and diversions may prevent access to critical foraging habitats for fish and other aquatic organisms. Thus, the effects of perching today may be quite different from the effects of perching prior to European settlement; and some of the changes may have reduced the functions of ecosystems that evolved under conditions of unimpeded water flows. To better understand how estuary and floodplain alterations may have affected ecosystem functions, better data are needed both on historical ecosystems of the Klamath estuary, and on the locations and nature of alterations to the estuary and nearby landscapes (see "Opportunities for further investigation" below).

Dam operations on the Klamath River, though far upstream, could affect estuary mouth opening, perching and closure in the estuary. Dam operations could alter mouth dynamics through reductions in summer flows, changes to sediment transport, changes to the magnitude and timing of peak flows, or other changes to river flow and sediment characteristics. Analyses of the effects of dam operations or dam removal on the Klamath spit and estuary mouth were beyond the scope of this study, but they deserve attention (see "Opportunities for further investigation" below).

Data recommendations

This study's mouth closure analysis and spit assessment identified several immediate data gaps related to this specific assessment, which are listed below. Filling these gaps would advance the understanding of estuary mouth behavior:

- Local nearshore wind and wave gauges to monitor wind and waves on a continuous basis, allowing the calculation of the closure index (S) and the berm height (h_{berm})
- Regular measurements (monitoring) of berm height (h_{berm}) using traditional elevation survey methods, photogrammetry, or terrestrial LIDAR
- Combined analysis of estuary water levels and estuary mouth photographs to detect perching, closure, and opening events
- Identification and mapping of water flow barriers in the estuary and floodplain which affect inundation extent during perching events (see "Opportunities for further investigation" below)

Further analyses of mouth configuration and its controlling factors

Data on ocean tides could enhance the mouth configuration analysis. These data are available, but we did not initially include them in our analysis; only after our analysis of the series of events did we conclude that the specific timing of discharge events in relation to wave power and ocean tide level may play an important role in the persistence of a breach. Therefore, we recommend adding ocean tide data to future analyses of estuary mouth configuration and its controlling factors.

As directed by our scope of work, this analysis was focused on development and validation of a conceptual model the spit, including identification of hydraulic behaviors correlated with mouth configuration changes. As described above, this involved two steps: 1) identifying specific mouth reconfiguration events; and 2) analyzing the controlling factors associated with those events. In other words, our analysis proceeded from a starting point of known mouth reconfiguration events.

Ultimately, however, resource management in the estuary would benefit from the ability to predict mouth reconfigurations such as mouth closure and perching, rather than analyzing events after the fact. To generate a predictive model, future assessments might be more efficiently performed by looking for hydraulic behaviors that indicate perching (such as high, nontidal water levels) and cross-referencing them to the Tribe's new, high-frequency photographic record of the estuary mouth. This would allow documentation of a larger number of events, which in turn may allow development of a predictive relationship for mouth closure and breaching through statistical analyses of these larger datasets. In addition, identifying a larger number of mouth perching and closure events, followed by analysis of monitoring data for perched or closed versus open conditions, will help determine how these events affect estuary functions. The next section provides some examples of monitoring to generate data that could be analyzed in this way.

Opportunities for further investigation

The morphological behavior of the mouth provides insight into how water levels in the estuary are controlled now and how they may will change in the future, but it only addresses part of the system behavior. As described in "Impacts of mouth perching and closure" above, mouth configuration interacts with many other characteristics of the Klamath estuary system to provide valued ecosystem services and habitat for plants, animals and people. To better understand these interactions and plan for climate change adaptation in the Klamath estuary, important avenues of further study include:

- Effects of perched water levels on wetlands, floodplains, and riparian areas in the estuary
    - *How are wetland and floodplain habitat conditions currently affected by mouth perching or closure?* As described above ("Impacts of mouth perching and

closure"), perching or closure can affect several controlling factors in these ecosystems. Long-term monitoring of these controlling factors (such as water level, water temperature and salinity, groundwater level, and groundwater salinity) at multiple locations in the estuary and its tributary streams, followed by careful analysis of their values during perched or closed conditions versus open conditions, would help determine the effects of mouth state on habitat conditions and functions for fish and many other organisms using the estuary. The knowledge gained would also be useful in improving wetland mapping in the estuary, since salinity and frequency of inundation are used in classifying wetlands.

- Historic conditions and hydrologic alterations in the estuary
    - *What were the historical habitat conditions in the estuary (prior to European settlement)?* Mapping of historical vegetation (dominant species and associations) and habitat types (e.g. wetlands) would greatly assist understanding of human impacts to the estuary. Mapping historical vegetation would allow quantification of human impacts to the estuary such as conversion of forests and shrublands to farm fields and developed uses. These vegetation changes directly affect wildlife habitat, and also alter wetland hydrology (including groundwater levels), water temperatures (through loss of streambank shading), and other ecosystem drivers.
    - *How have wetland and floodplain alterations affected water flows and inundation during perched and closed conditions? How have these changes affected fish and wildlife habitats and other ecosystem functions?* As described above, alterations that change the extent of inundation during perching, or which divert flows, can strongly affect wetland, floodplain, and riparian ecosystem functions. Mapping of flow barriers and other alterations such as levees, restrictive culverts, flood gates, filled lands, and road/railroad embankments would greatly assist understanding of the degree of change in the estuary. Combining such mapping with historical habitat mapping would provide a powerful base for assessing human impacts and restoration potential.
- Changes to water quality associated with mouth closure and perching
    - *How do perched conditions affect fish habitat characteristics and functions in the estuary?* As described in "Impacts of mouth perching and closure" above, perching may affect physical and chemical characteristics of estuary waters (e.g. salinity, temperature, and stratification), which in turn may affect fish habitat functions. Long-term monitoring of these water quality parameters at multiple locations in the estuary and its tributary streams, followed by careful analysis of their values during perched or closed conditions versus open conditions, will help determine how change in mouth configuration may affect fish.
    - *How do water quality changes associated with perching and closure affect estuarine plant and macroinvertebrate communities?* Short term changes may have only temporary effects, but frequent events like partial perching are likely to be important in structuring the living communities that form in and around the estuary.

- Sediment transport in the estuary
    - *How do long-term cycles in sediment transport from rare hydrologic events shape the behavior of the estuary?* As mentioned above, this study did not include analysis of large river floods, but such events can reshape estuary features and strongly affect distribution of habitats and the organisms that depend on them.
    - *What are the implications of dam removal on the sediment transport regime in the estuary?* Changes to estuarine sedimentation may occur with dam removal, with associated changes to estuary habitat structure and function.
- Effects of dam operations and dam removals on estuary mouth dynamics
    - *What have been the likely effects of dam operations on mouth configuration (mouth opening, perching, and closure) in the past? How might dam removals affect these events in the future?* As described in "Impacts of mouth perching or closure" above, dam operations that affect river flows (low flows, peak flows, timing) may also affect mouth dynamics. Changes to mouth dynamics, in turn, could affect estuary functions as described above.

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Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Appendix 1. Klamath River mouth configuration time series

This appendix contains a time series of Klamath River mouth reconfiguration events, along with physical data for each event (wave power, river flow, and water surface elevation).

Note that y-axis range varies from one event to another.

Reference data

Tables 1 and 2 provide reference data to assist interpretation of the time series data below.

Water surface elevations ("WSE") were obtained from the Yurok Tribe from their Requa boat launch gauge. Tidal datums in Table 1 were computed for the tribe by JOA Surveys using the Tribe's water surface elevations at that gauge, and converted to NAVD88. The computation used a fifth order Butterworth Lowpass filter with a five month long, 15-minute interval dataset of water surface elevations in the Klamath estuary from March 2008 through August 2008.

Table 1: Tidal datums at Requa boat launch gauge

Datum	Elevation (m NAVD88)
MHHW	2.23
MHW	2.06
DTL	1.47
MTL	1.48
MSL	1.45
MLW	0.91
MLLW	0.70

Table 2: Statistical measures of time series parameters. Flow (river discharge) is from the USGS gauge 1530500 near Klamath; wave power is from NOAA's buoy at Cape Mendocino.

Parameter	Mean	Median	Max	Min
Flow, Q (m^3/s)	368	144	11,890	
Wave Power (kW/m)	66.4	44.4	897.1	1.5

Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 1: 9/25/2007 through 10/03/2007

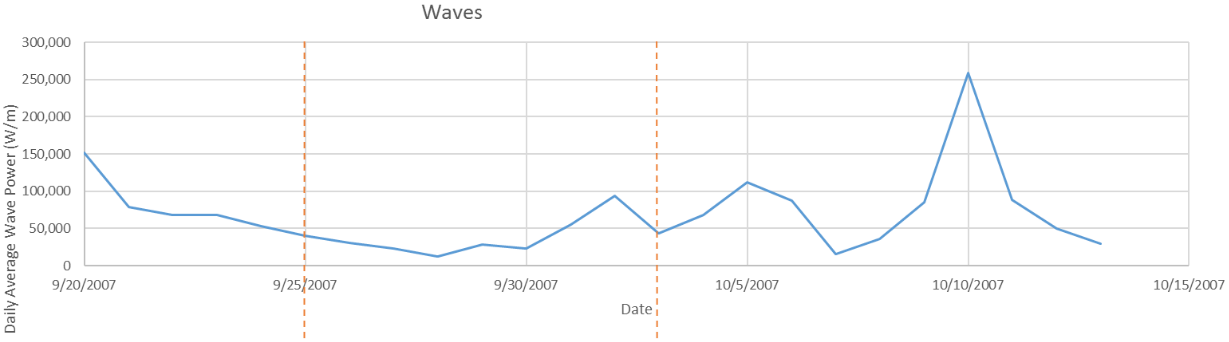
Opening

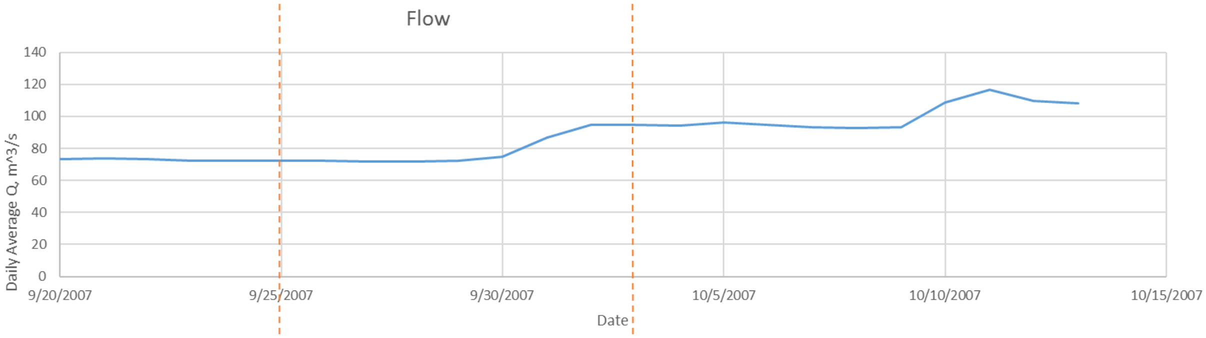
Perched chute arrangement of the mouth from River Right to River Center changes to opening flushed straight on River Right.

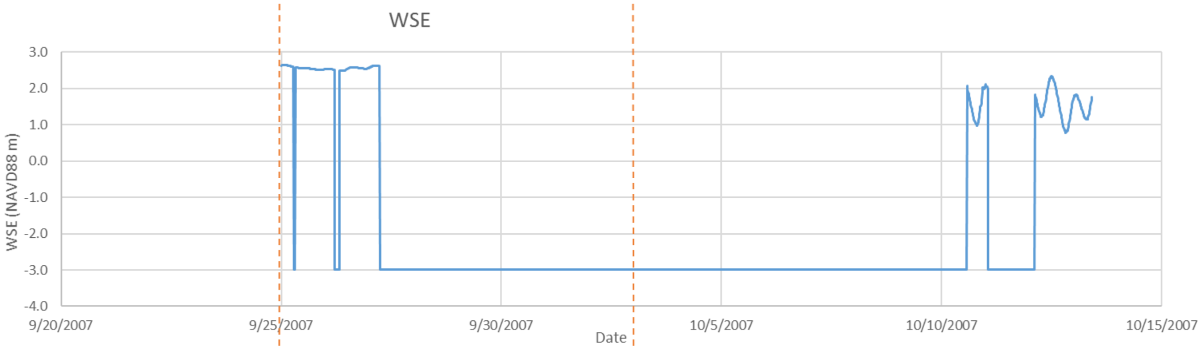
Figure A1: Klamath River Estuary mouth 9/25/2007 (left) and 10/03/2007 (right).

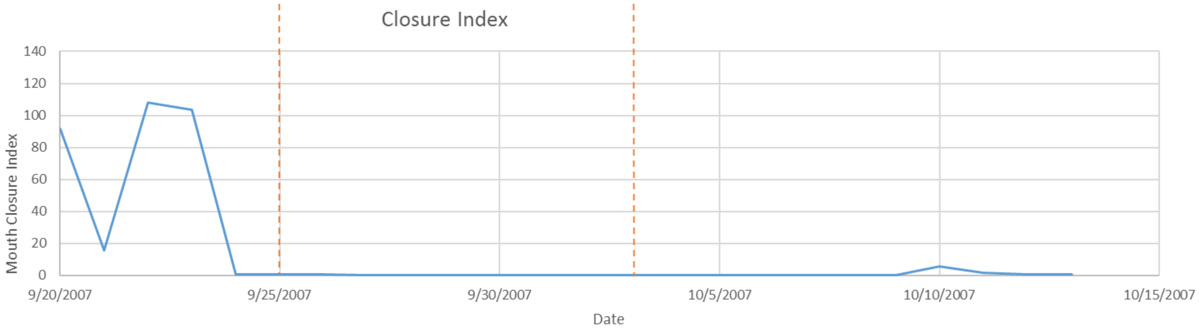
Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

- **Waves:** Wave energy is near average (66.4kW/m) for most of the period, peaking at 94 kW/m on 10/2.
- **Flow:** Increased from 72 m^3/s to 95 m^3/s across the period of interest. About 75 m^3/s appears typical for the preceding 1-2 months. Flow continues to increase after the mouth straightens.
- **WSE:** The data is incomplete over the period of interest; however, tidal signal is absent when the mouth is a perched chute and present after the mouth is straightened. (Note: negative WSE values represent periods lacking data.)
- **Closure index:** The closure index is high at the start of the period but cannot be computed for the whole event due to missing water level data.









Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 2: 12/09/2008 through 2/27/2009

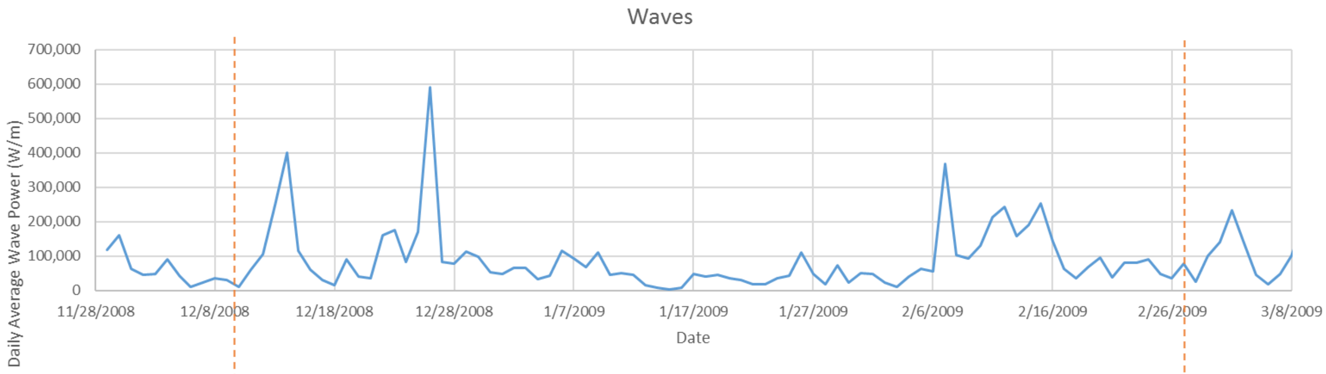
Opening

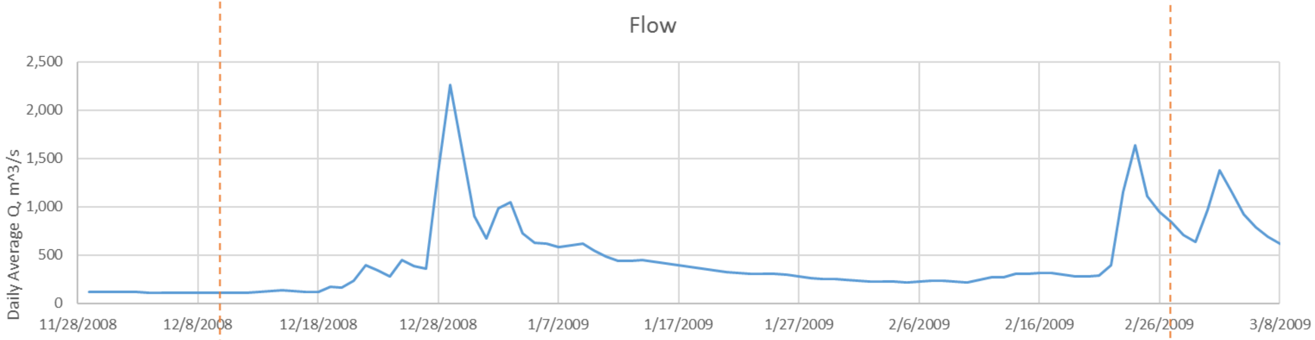
River Right to River Center chute arrangement changes to River Center to River Right chute, then trends back to straight channel on the River Right valley wall.

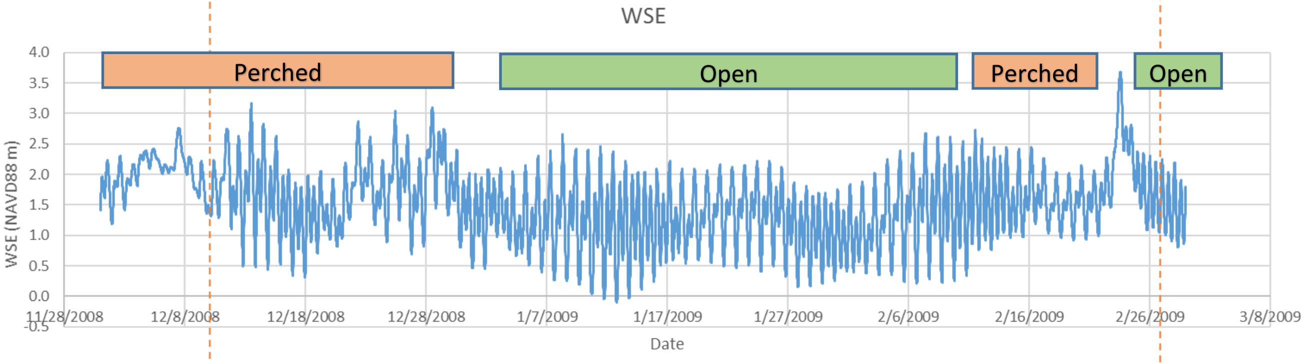
Figure A2: Klamath River Estuary mouth 12/9/2008 (left), 1/23/2009 (center), and 2/27/2009 (right).

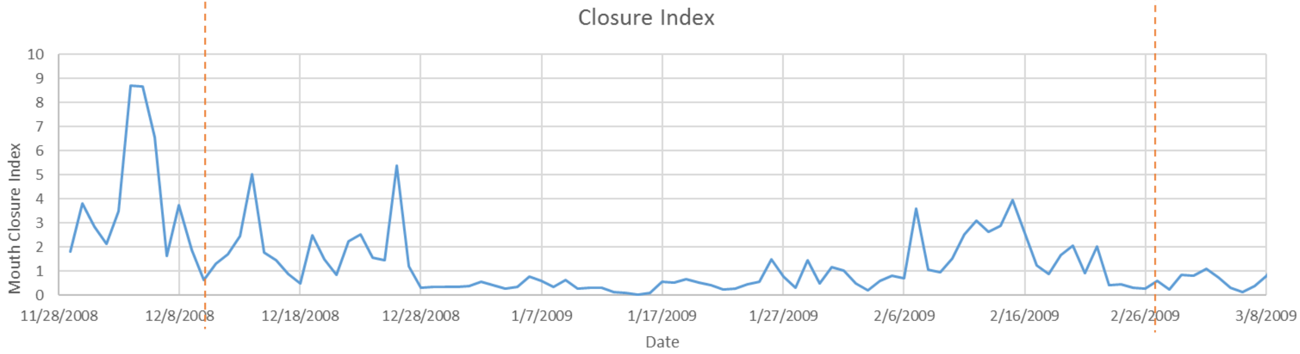
Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

- **Waves:** Three surges in wave power (two ~400 kW/m and one ~600 kW/m) occur between the first and second photographs for the period of interest.
- **Flow:** First two photos bracket a moderate storm event (peak at 2260 m^3/s on 12/29/08). Moderate storm flow of 1634 m^3/s occurs 2/24/09, before final photo (2/27/09).
- **WSE:** The tidal signal is muted before 12/29/08, when the mouth was a chute.
- **Closure index:** The closure index spikes several times (~8.5, 5, 5.5) early on; falls mostly between 0 and 1 for the month of January; and then rises again to 3 to 4 in the beginning of February.









Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 3: 10/12/2009 through 10/19/2009

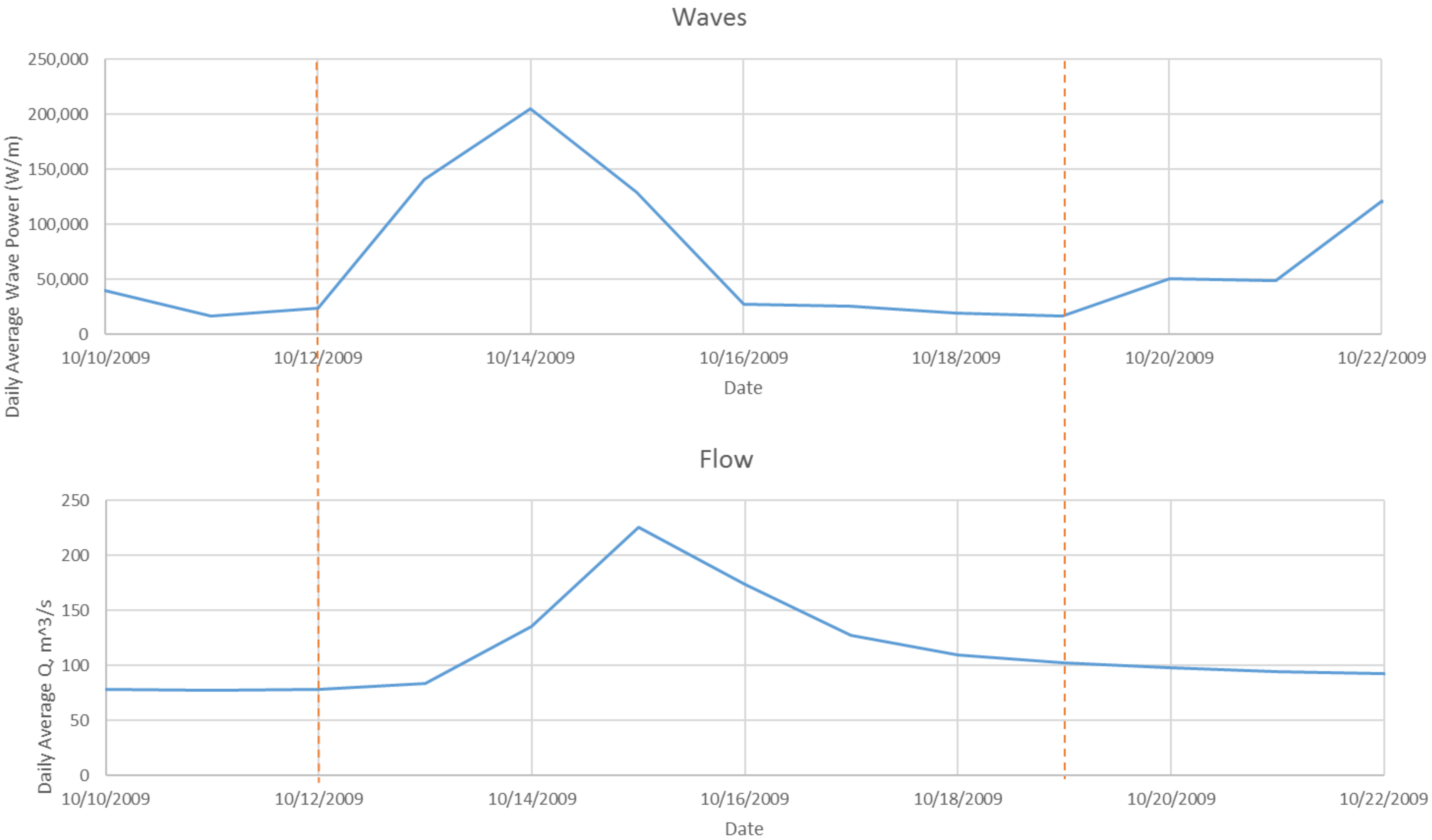
Perching and re-opening

Perched River Right to River Center chute nearly closes, and then breaches as a centered River Center to River Right arrangement.

Figure A3: Klamath River Estuary mouth 10/12/09 (left), 10/15/09 (center), and 10/19/09 (right)

Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

- **Waves:** There is a substantial surge in wave power to 205 kW/m on 10/14/09, directly before the moderate flow spike.
- **Flow:** Discharge begins at 78 m^3/s, peaks on 10/15/09 at 225 m^3/s, and ends at 102 m^3/s.
- **WSE:** Incomplete data for the period due to instrument malfunction.
- **Closure index:** The index cannot be calculated for the period of interest due to incomplete WSE data.



Event 4: 10/18/2010 through 10/27/2010

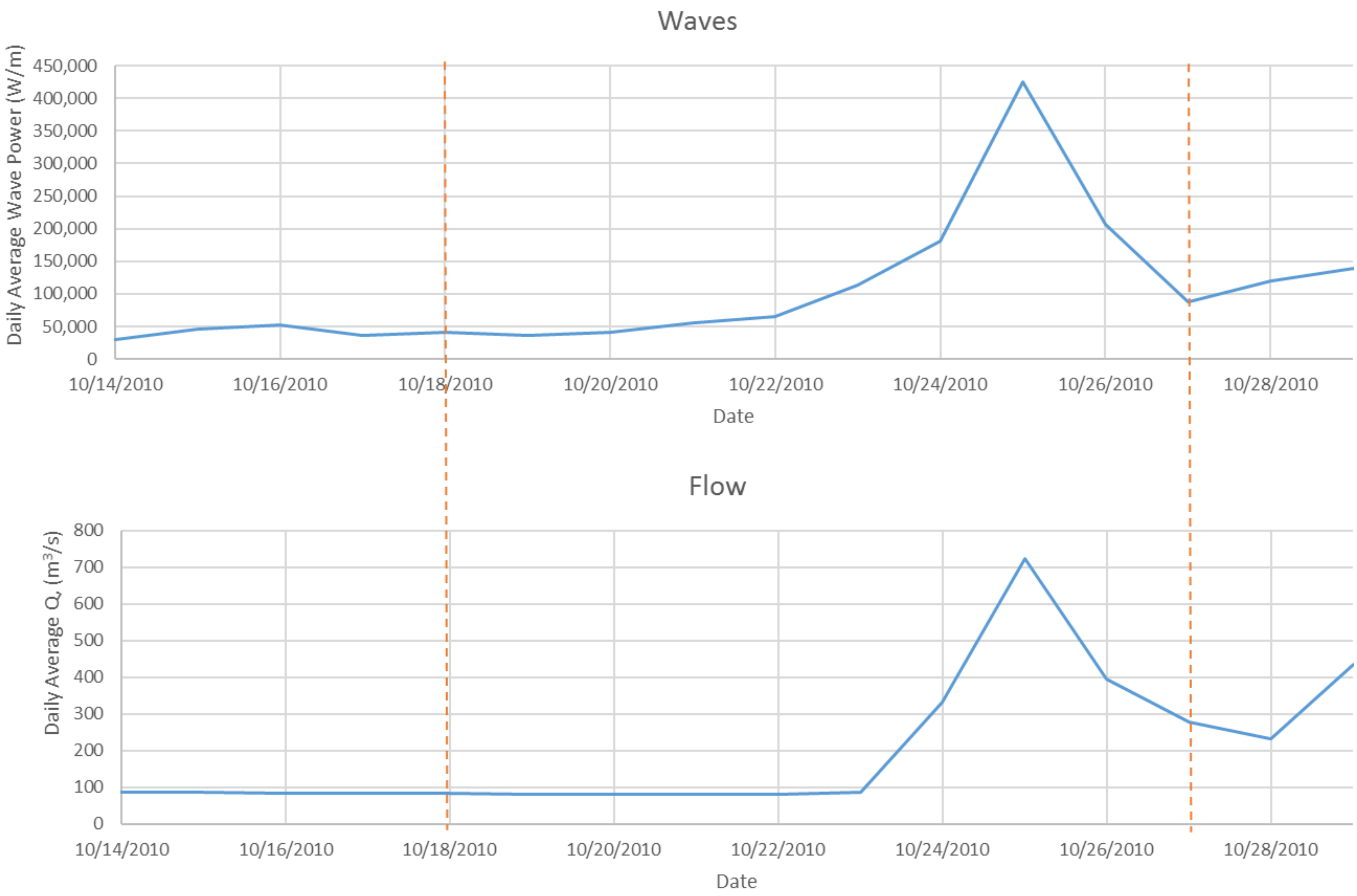
Opening

River mouth starts as a River Right to River Center arrangement, nearly closes, then flushes and establishes a deep breach on River Right.

Figure A4: Klamath River Estuary mouth 10/18/2010 (left), 10/24/2010 (center), and 10/27/2010 (right).

Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

- **Waves:** There is a substantial spike in wave power of ~ 424 kW/m on 10/25/10.
- **Flow:** Discharge begins at 84 m^3/s, peaks at 725 m^3/s on 10/25/10, and then drops to 278 m^3/s by 10/27/10.
- **WSE:** No data for period of interest.
- **Closure index:** The closure index cannot be calculated for the period due to lack of WSE data.



Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 5: 8/23/2011 through 11/8/2011

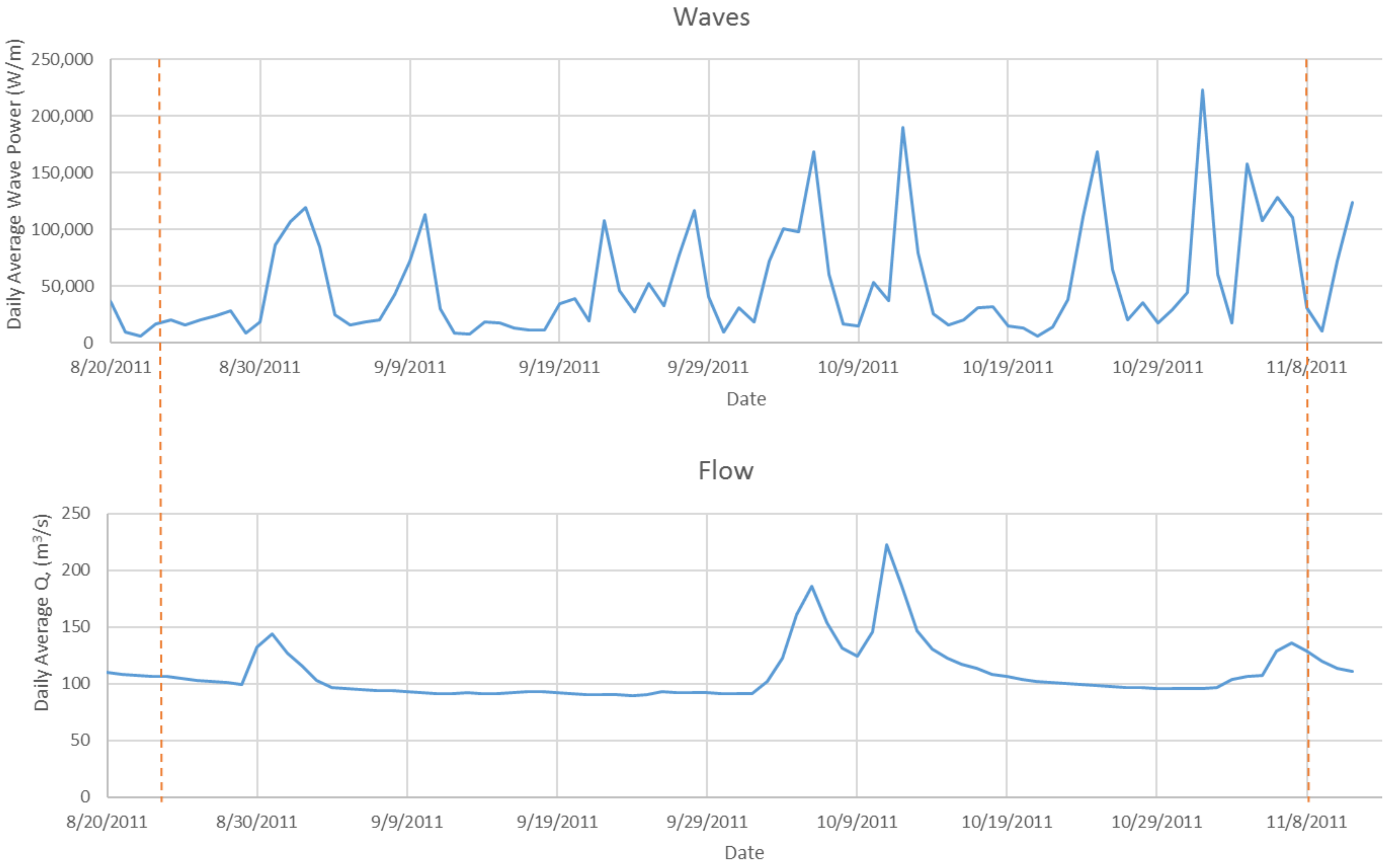
Perching

Straight mouth opening all the way River Right transforms into chute opening from River Right to River Center.

Figure A5: Klamath River Estuary mouth 8/23/2011 (left) and 11/8/2011 (right).

- **Waves:** Wave power is highly variable and often substantial over the period.
- **Flow:** Discharge begins at 107 m^3/s, peaks at 222 m^3/s on 10/11/11, and finishes at 129 m^3/s. Discharge averages 109 m^3/s over the roughly 2.5 month time span. Continuous wave power appears to cause the mouth to form the chute.
- **WSE:** No data for the period.
- **Closure index:** The closure index cannot be calculated, due to lack of WSE data for the period.

Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge



Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 6: 11/22/2011 through 11/29/2011

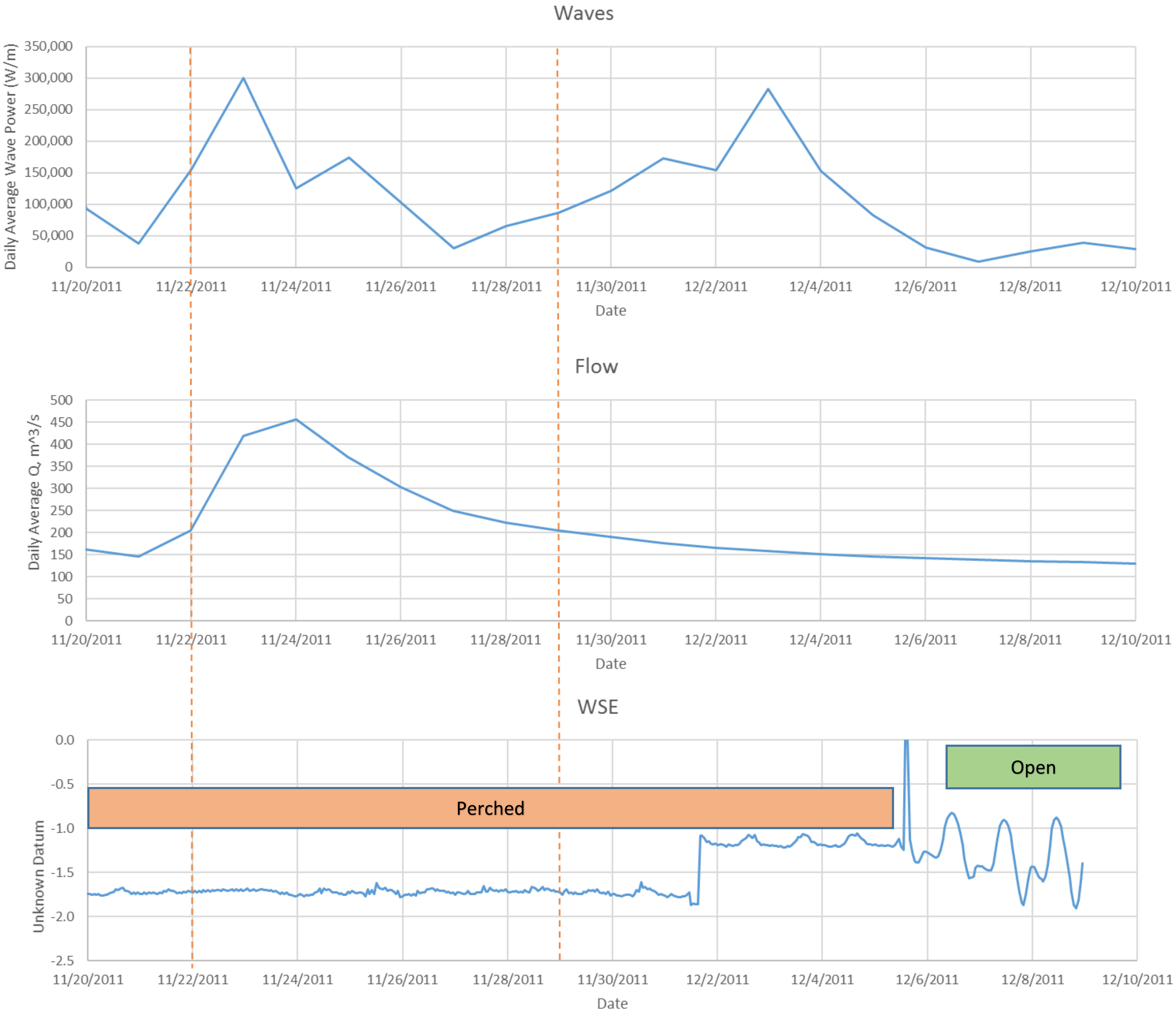
Opening

Chute arrangement of the mouth from River Right to River Center changes to opening flushed straight on River Center.

Figure A6: Klamath River Estuary mouth 11/22/2011 (left) and 11/29/2011 (right).

- **Waves:** Wave power is high at the beginning of the period and drops off substantially by the end.
- **Flow:** Discharge begins at 204 m^3/s, peaks at 456 m^3/s on 11/24/11, and finishes at 205 m^3/s. The peak flow appears to cause the mouth to straighten.
- **WSE:** Due to apparent equipment malfunction, data cannot be expressed on the common elevation datum (NAVD88) – that is, the datum is unknown, which prevents calculation of the tidal prism. A clear change from absence to presence of tidal signal is observable when the mouth has straightened. The discontinuity in WSE at 12/2/11 is due to equipment malfunction, preventing conversion of elevations to the common datum (NAVD88).
- **Closure index:** The closure index is incomplete for the period.

Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge



Event 7: 12/18/2011 through 12/27/2011

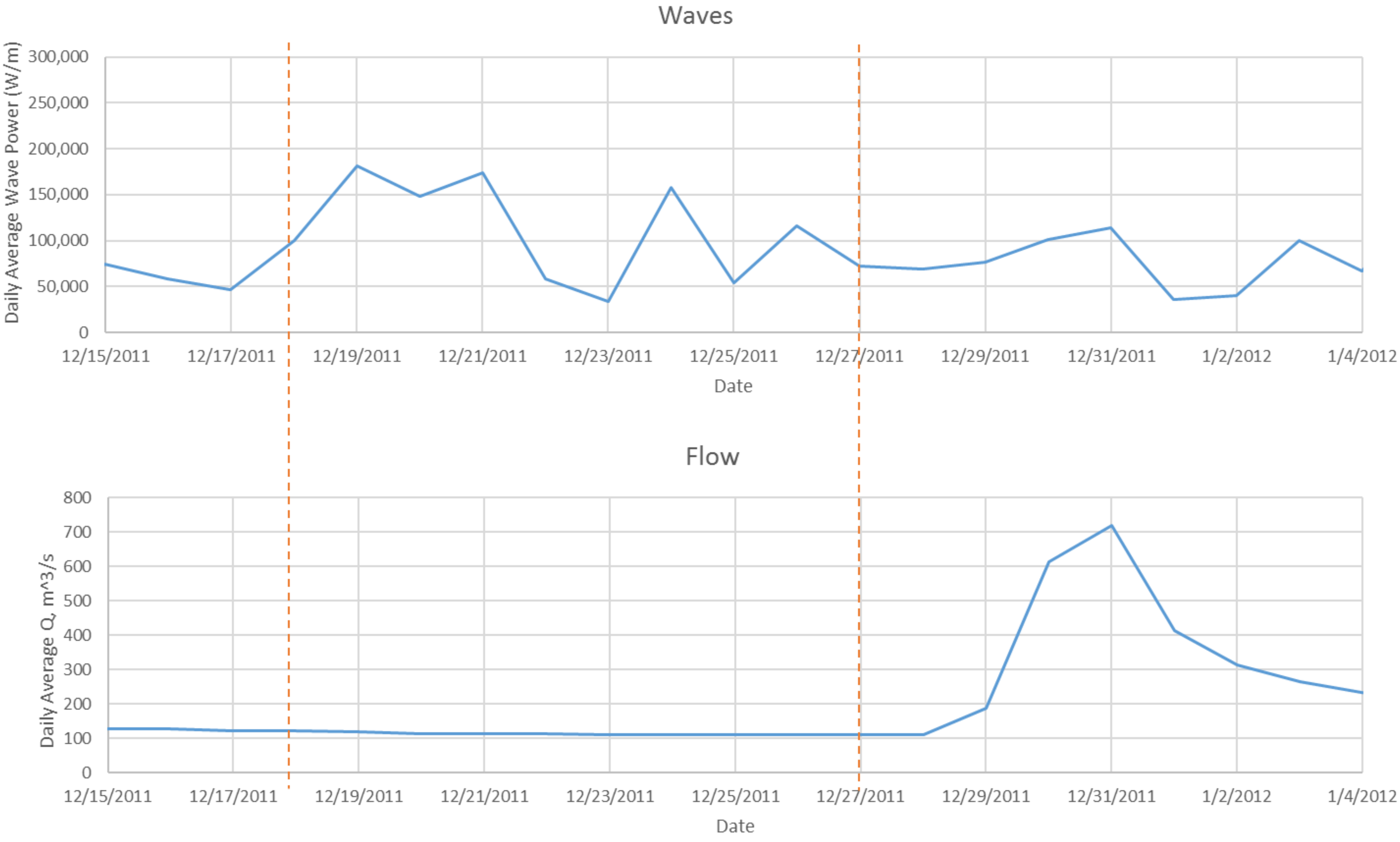
Opening

Mouth perches in River Right to River Left chute, then breaches River Center.

Figure A7: Klamath River Estuary mouth 12/18/2011 (left) and 12/27/2011 (right).

- **Waves:** Wave power is highly variable and often substantial over the period
- **Flow:** Discharge reduces steadily from 123 m^3/s to 110 m^3/s over period. Peak flows occur after mouth has straightened.
- **WSE:** No data for the period
- **Closure index:** The closure index cannot be calculated for the time period due to lack of WSE data.

Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge



Event 8: 1/17/2012 through 1/20/2012

Opening

Perched chute arrangement of the mouth opening from River Right changes to River Center flushed straight.

Figure A8: Klamath River Estuary mouth 1/17/2012 (left) and 1/20/2012 (right).

- **Waves:** Wave power peaks for the period near 187 kW/m on 1/19/12
- **Flow:** Discharge increases from 130 m^3/s to 1727 m^3/s over the period of interest, and peaks at 2540 m^3/s on 1/21/12.
- **WSE:** Muted tidal signal is observable during the beginning of the period; the full tidal signal returns on 1/19/12 when the mouth straightens. Water level in the estuary exceeds MHHW by nearly 2 m prior to the opening event.
- **Closure index:** Closure index peaks at ~32 just before the period, drops to 10.3 by the time of the first photo, then drops nearly to zero as the mouth straightens and opens.

Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Appendix 1. River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 9: 10/16/2012 through 10/23/2012

Perching

Straight mouth opening at River Right transforms into chute opening from River Right to River Center.

Figure A9: Klamath River Estuary mouth 10/16/2012 (left) and 10/23/2012 (right).

- **Waves:** Wave power peaks at ~104 kW/m on 10/17/12 and drops off to average or below average levels over the period.
- **Flow:** Discharge peaks at 95 m^3/s 10/17/12, drops to typical (1 month) preceding condition of 74 m^3/s on 10/21/12, and rises again to 120 m^3/s on 10/24/12.
- **WSE:** Tidal signal is muted after 10/21/12 as the chute forms and the mouth perches. Water level in the estuary exceeds MHHW during the perching event.
- **Closure index:** The closure index spikes at the end of the period.

River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 10: 10/30/2012 through 11/13/2012

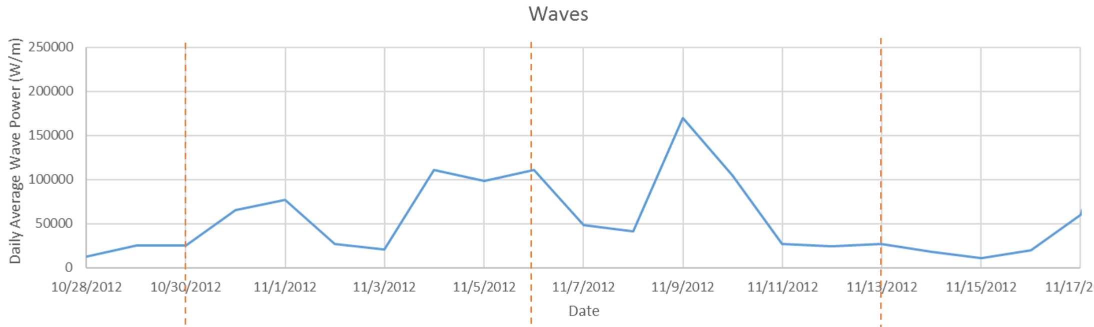
<u>Opening</u>

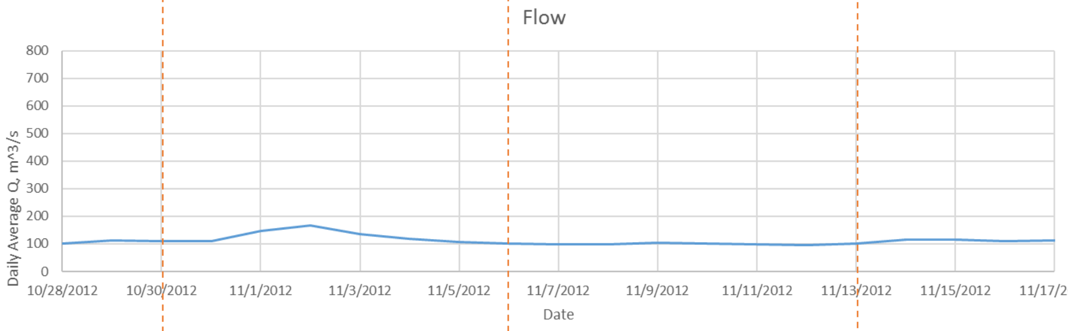
Perched chute opening from River Right to River Center on 10/30/2012. Mouth is obscured 11/6/2012, but visibly open at River Center 11/13/12.

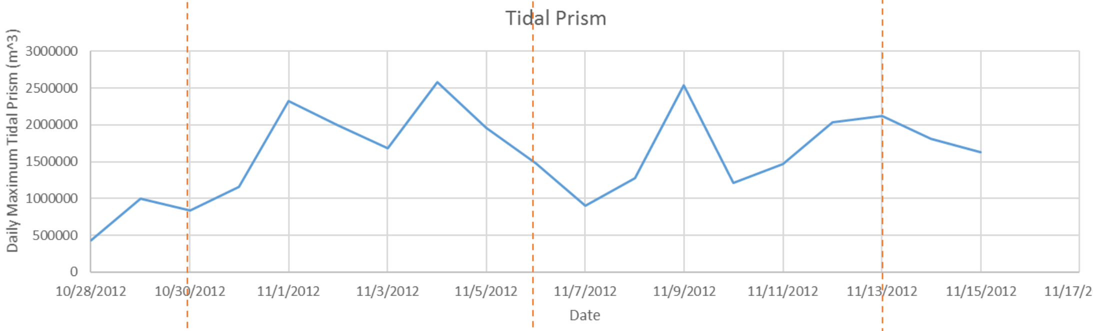
Figure A10: Klamath River Estuary mouth 10/30/2012 (left), 11/6/2012 (center), and 11/13/2012 (right).

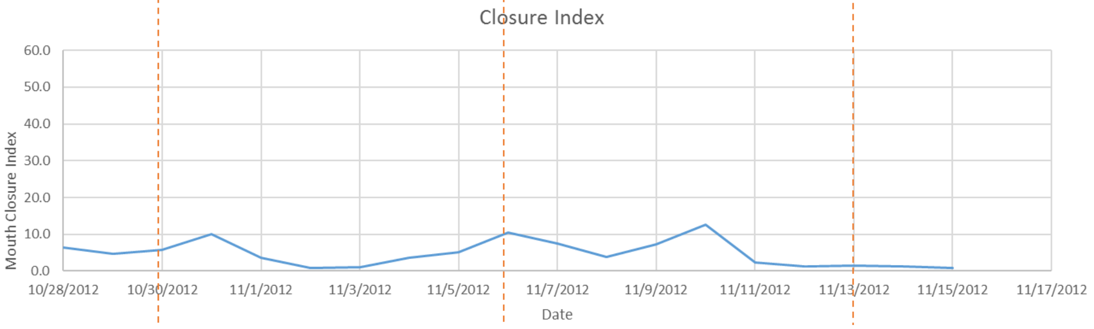
- **Waves:** Wave power is moderate for the period, and peaks at ~169 kW/m on 11/9/12 dropping off to <25 kW/m by 11/11/12 for the rest of the period.
- **Flow:** Discharge begins at 110 m^3/s, peaks at 167 m^3/s on 11/2/12, drops to 98 m^3/s by 11/7/12, then remains relatively constant through 11/13/12.
- **WSE:** Tidal signal is muted through 10/30/12 when mouth is perched. The tide signal returns strongly by 11/2/12 as mouth reopens.
- **Closure index:** Closure index fluctuates between 0 and 13 for the period.

River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge



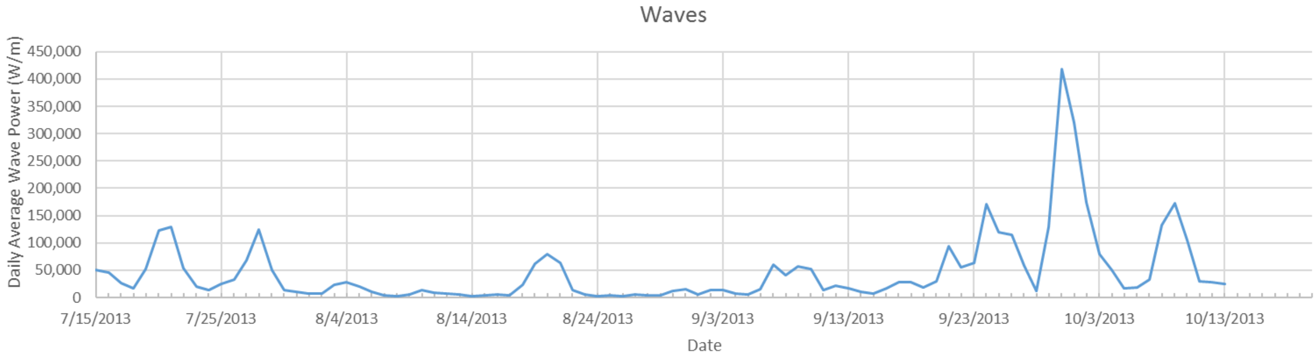


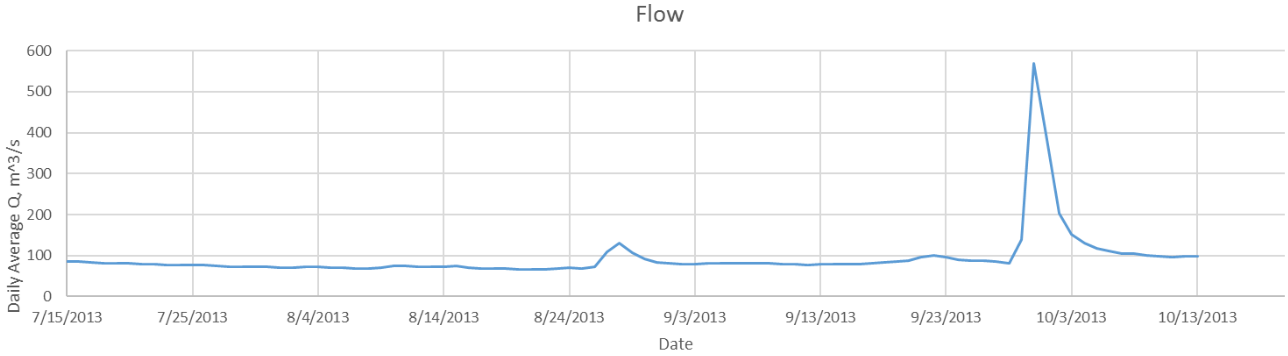


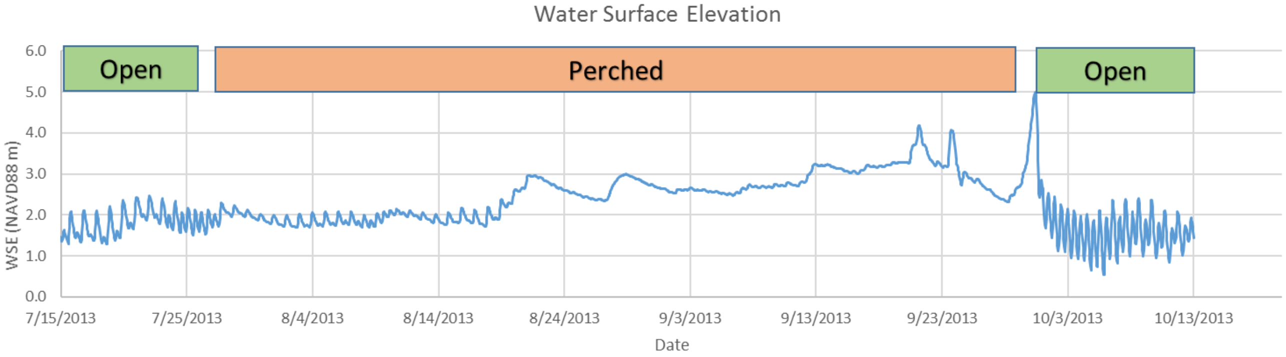


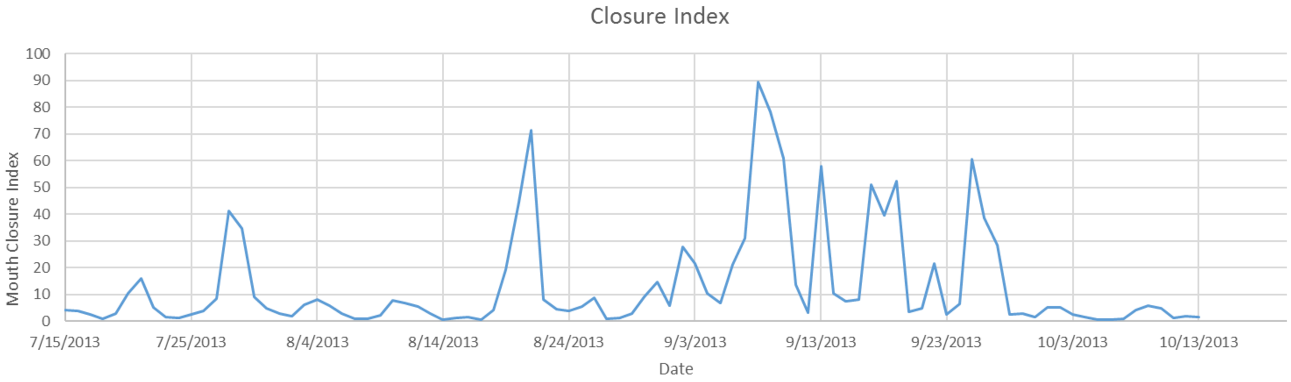
River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 10a: 8/7/2013 through 10/16/2013: Perching and re-opening. See main body of report for narrative and photos (Figure 11).









River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 11: 11/5/2013 through 1/7/2014

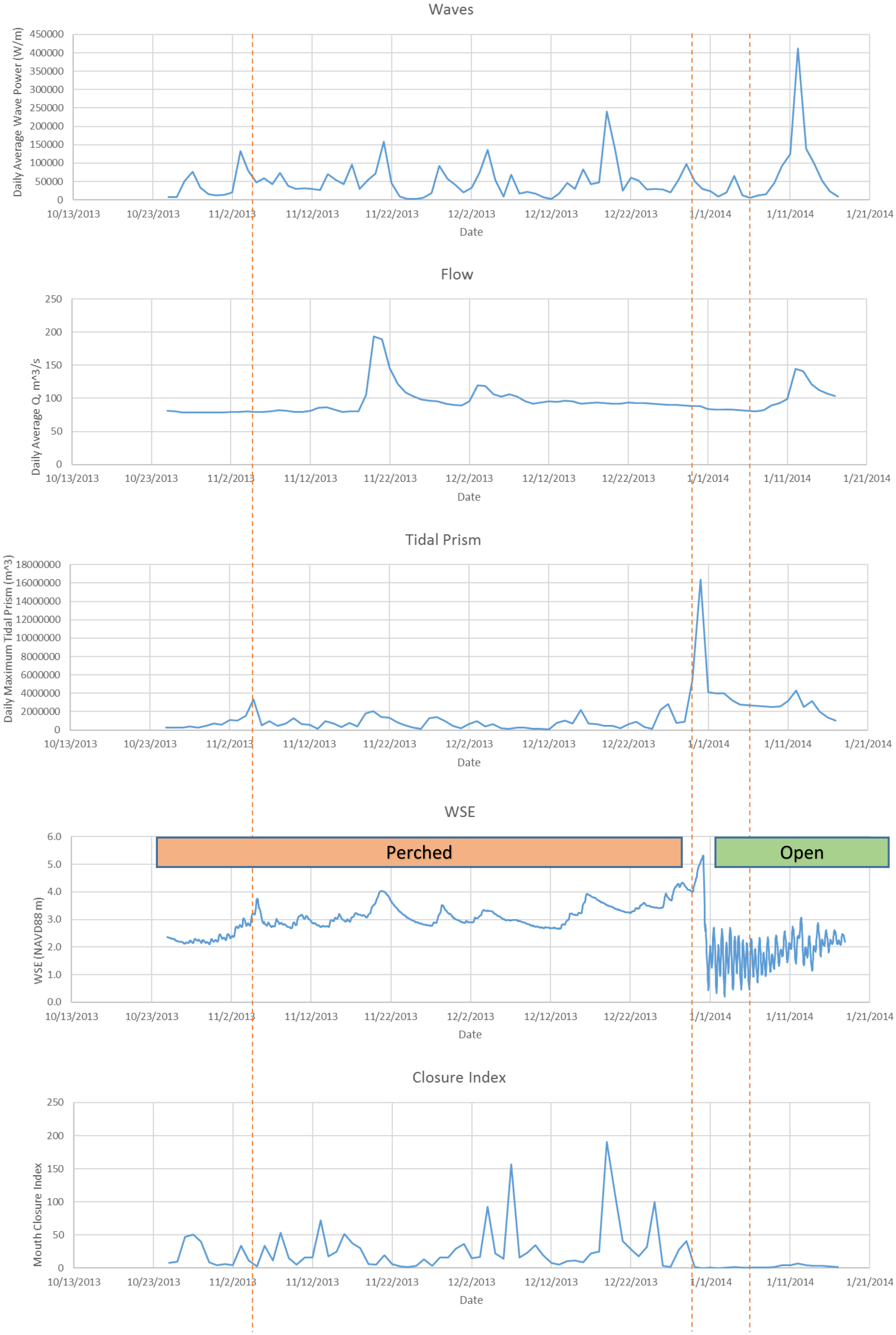
Perching and re-opening

Mouth nearly closes in the first photo and perches off and on until a full closure on 12/30/2013, and then re-breaches in the center. Mouth perches off and on throughout January 2014.

Figure A11: Klamath River Estuary mouth 11/5/2013 (left), 12/30/2013 (right), and 1/7/2014 (bottom).

- **Waves:** Wave power fluctuates near the average over the period; it peaks near 240 kW/m on 12/19/13.
- **Flow:** Discharge starts at 80 m^3/s, peaks at 194 m^3/s on 11/20/13, lightly spikes to 119 m^3/s again on 12/03/13, but generally remains below 100 m^3/s for the period of interest. Flow is 89 m^3/s at the time of full closure and continues to descend to 80 m^3/s by the end of the period. Average discharge is 96 m^3/s.
- **WSE:** Tidal signal is absent/muted until 1/1/14 when the mouth is perched. Water level is at a maximum during the period the mouth is closed, ultimately reaching 3 m above MHHW. The full tidal signal is re-established once the mouth is straightened.
- **Closure index:** The closure index fluctuates dramatically and is mostly above 10 for the period. It peaks 12/7/13 at 142, 12/19/13 at 108, 12/25/13 at 86 and 12/29/13 at 34.

River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge



River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 12: 9/30/2016 through 10/16/2016

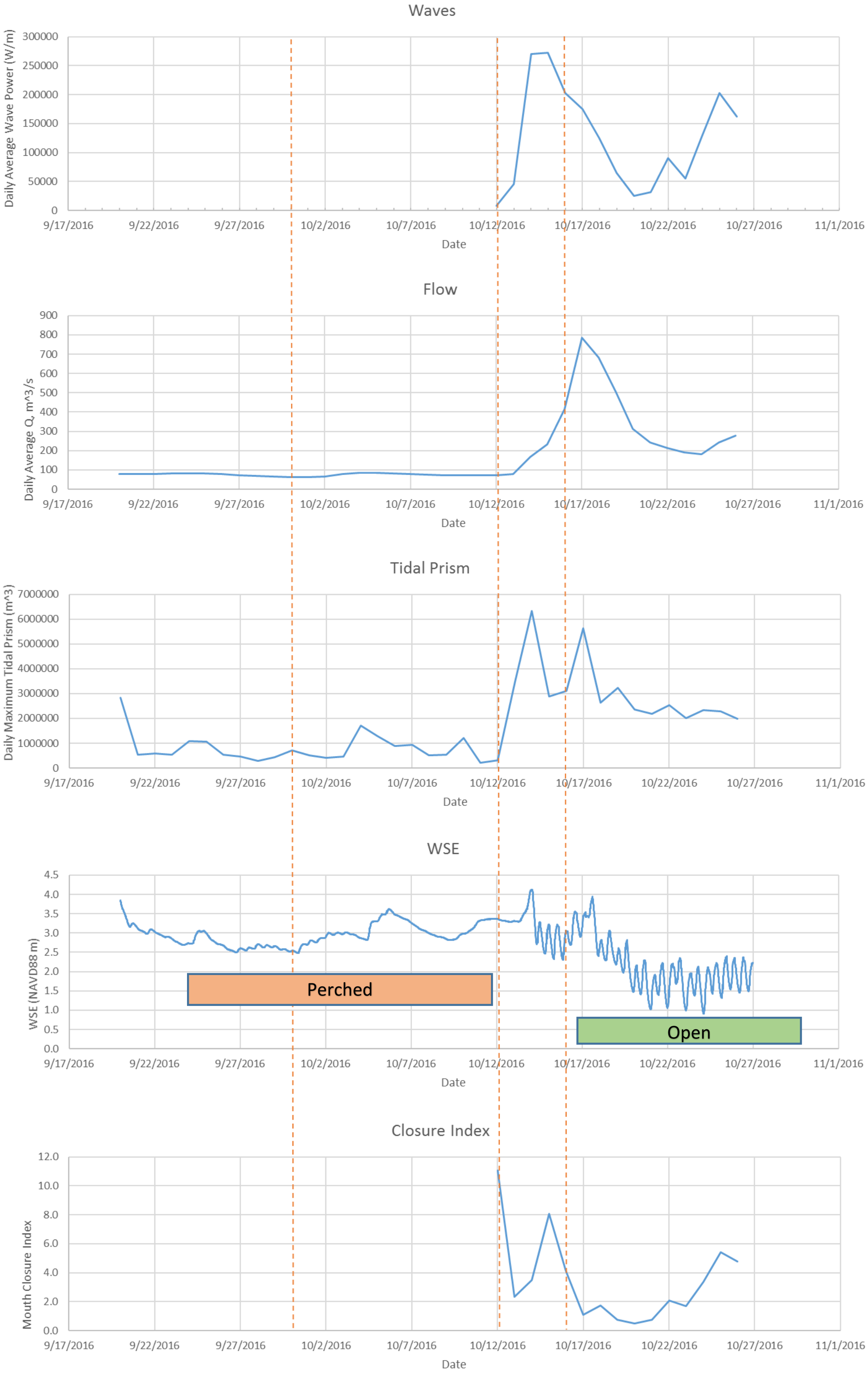
Perching and re-opening

Mouth trends in a River Right to River Left chute, perching and nearly closing throughout late August, September, and early October. Mouth closes definitively 9/30 at 6 pm, and 10/12 at 3 pm. Mouth is definitively open 10/16 at 6 pm.

Figure A12: Klamath River Estuary mouth 9/30/2016 (left), 10/12/2016 (center), and 10/16/2016 (right).

- **Waves:** Wave power data is unavailable until 10/12/16, after which it climbs to peak at ~270 kW/m on 10/15/16.
- **Flow:** Discharge begins at 62 m^3/s, is 71m^3/s on 10/12/16, and climbs to 416 m^3/s by 10/16/16 peaking after the last photo at 784 m^3/s on 10/17/16. Discharge remains between 200 and 1000 m^3/s through the end of October 2016.
- **WSE:** Tidal signal is muted through 10/14/16 as the mouth is perched or closed. There is a full tidal signal as the mouth opens following the peak discharge on 10/16/16. The water level in the estuary exceeds MHHW by 1-2 m during the perching event.
- **Closure index:** The closure index is observable once the wave data becomes available, descending from a starting value near 10.

River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge



River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge

Event 13: 2/11/2017 through 3/5/2017

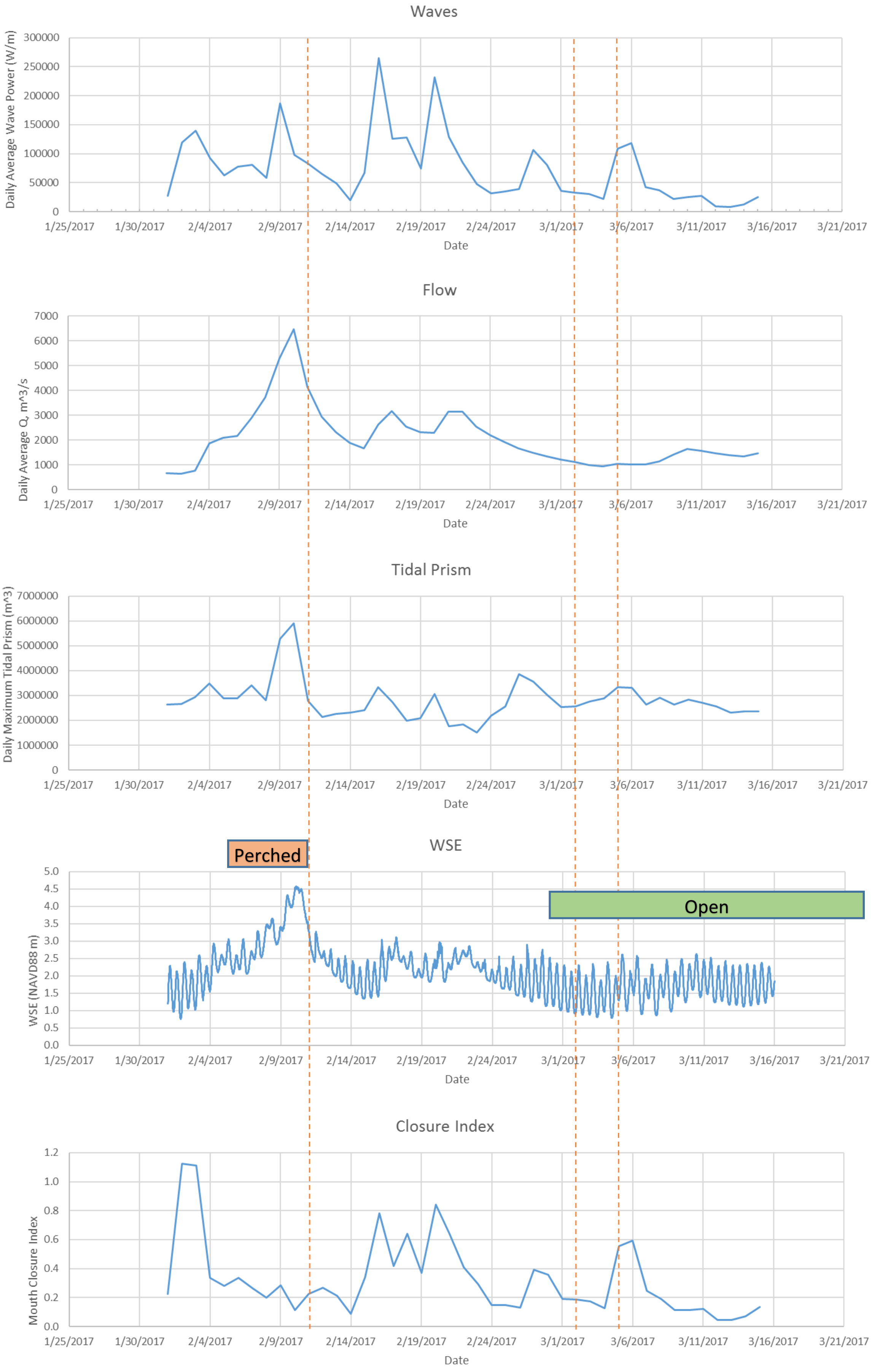
Perching and re-opening

A mid-channel bar forms in the main opening at the river mouth, which appears similar to mouth direction/angle switching behavior. Mouth remains open, and eventually the River Right side of the mid-channel bar fills in, confining flow to the River Left path.

Figure A13: Klamath River Estuary mouth 2/11/2017 (left), 3/2/2017 (right), and 3/5/2017 (bottom).

- **Waves:** Wave power followed a roughly average baseline with many substantial peaks, including one of 273 kW/m 2/16/17.
- **Flow:** Discharge dropped from 6456 m^3/s on 02/10/17 to 2945 m^3/s on 2/12/17. Discharge fluctuated between 950 m^3/s and 3200 m^3/s through the period, but the trend was downward and flow remained below 2000 m^3/s after 2/24/17.
- **WSE:** Tidal signal is not substantially dampened except during the high flow event, when WSE peaked more than 2 m above MHHW (on 2/10/17).
- **Closure index:** Closure index remains below 1 for entire period.

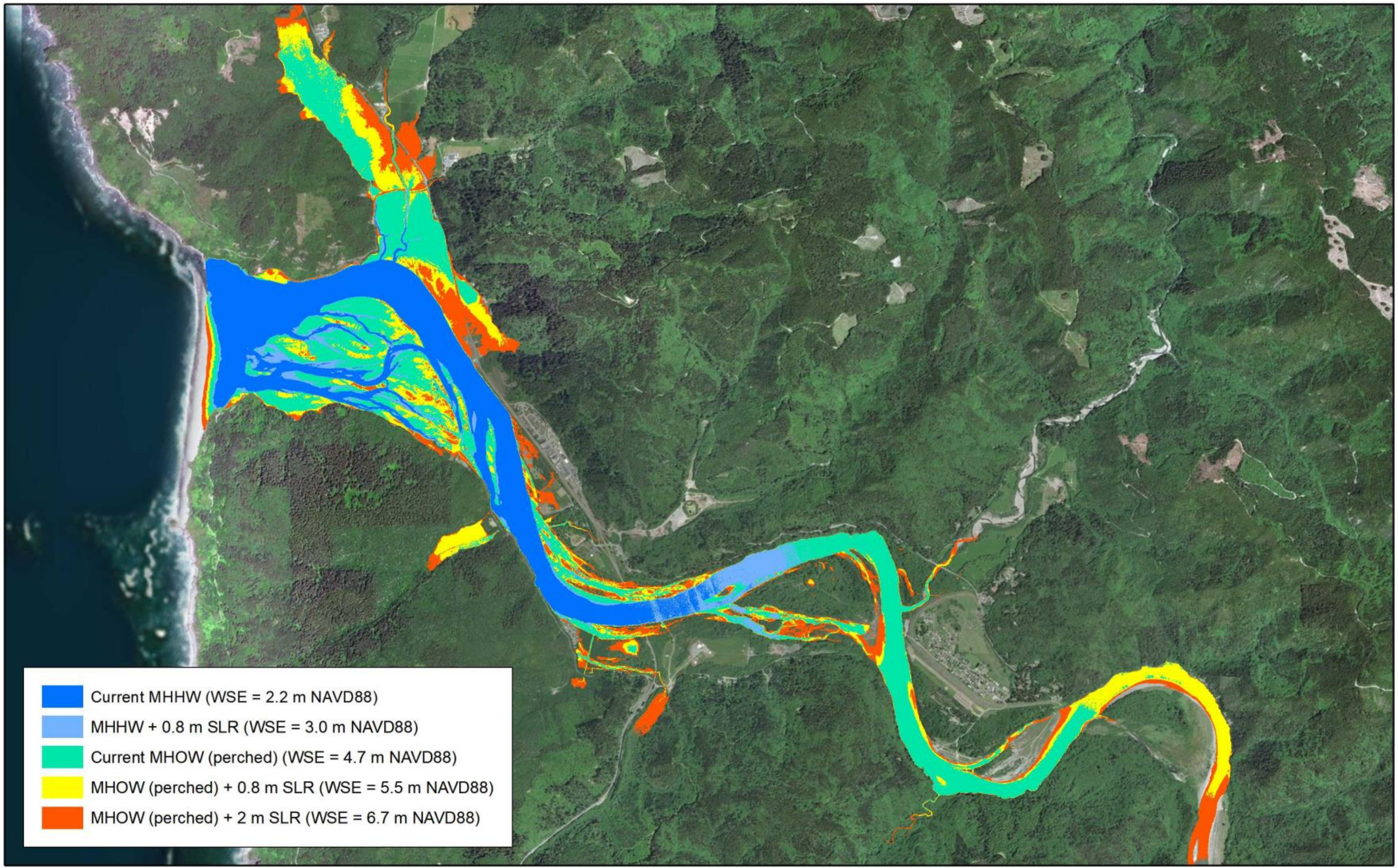
River Right and River Left are all facing downstream, towards the ocean
Wave data from offshore station at Cape Mendocino; water surface elevations from Requa boat launch gauge



Appendix 2. Map of potential inundation for current conditions and sea level rise scenarios

Klamath River Estuary: Areas potentially inundated under perched estuary mouth conditions and sea level rise scenarios

Colors indicate additional area inundated for each scenario (so each scenario includes areas inundated at all lower scenarios). Inundation map is based on a bathtub model and does not account for hydrodynamics, flow barriers, or major river flood events.



Prepared 1/16/2018 by the Estuary Technical Group, Institute for Applied Ecology and Wolf Water Resources under contract to the Yurok Tribe. See project report for details and references. Projection: NAD_1983_UTM_Zone_10N (WKID 26910). Mapped areas derived from LIDAR elevation models provided by the Yurok Tribe, and projected sea level rise from Griggs et al 2017 and NOAA (Technical Report 83). This product is for informational purposes only and is not intended for navigational, legal, engineering, or surveying purposes; it is provided with the understanding that conclusions drawn from the information are the responsibility of the user. ArcGIS 10.3.1, KRE_WSE_SLR_20180116.mxd. Institute for Applied Ecology, www.appliedeco.org, 541-753-3099.

WOLF WATER RESOURCES

Institute for Applied Ecology