MEMO

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Date:
August 21, 2015

ARCADIS Project No.:
RV009910.0000

Subject:
Delta Levees Investment Strategy:
Sea Level Rise Methodology

1   Overview

This memorandum describes the methodology used to account for the impact of potential future sea level rise on the Delta Levees Investment Strategy (DLIS) metrics and how those impacts are incorporated into the DLIS planning tool. A description of the approach used to account for the spatial variation of tide effects in the Delta and Suisun Marsh and prediction uncertainties are also included in this memorandum.

2   Sea Level Rise

Water levels in the Delta and Suisun Marsh at any given time are the result of a complex interaction between tide level at Golden Gate and the variable inflow of the rivers and streams that enter the Delta and Suisun Marsh. An increase in the average sea level at Golden Gate would alter the hydraulic conditions in the Delta and Suisun Marsh, which would increase the hydraulic stress on the levees and, assuming other levee conditions remain unchanged, would increase the annual likelihood of levee failure.

To address potential sea level change in the Delta, the DLIS team has adapted the methodologies presented in the Delta Risk Management Strategy (DRMS) Flood Hazard Report (DRMS, 2009). Section 5 of the DRMS report provides a method of determining water levels in the Delta or Suisun Marsh based on

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present day tide levels at Golden Gate and total Delta and Suisun Marsh inflows. Section 6 of the DRMS report provides a method of determining the effect of future sea level rise at any location in the Delta or Suisun Marsh based on a simplified hydraulic flow model and an assumed sea level increase. Excerpts from the DRMS report that describe these two methodologies are included as Attachments A and B.

To calculate the probabilities of levee failure and risk to people and assets, it is necessary to develop stage-recurrence curves at locations throughout the Delta and Suisun Marsh. Stage-recurrence curves define the return period (by annual probability of occurrence) for each potential water level at a location The DLIS team developed stage-recurrence curves for present day tide conditions and for the potential future tide conditions shown in Table 1. The values in this table are sea level increases relative to baseline (year 2000) sea levels at Golden Gate and were obtained from a National Research Council (NRC) report of potential future sea level rise (NRC 2012). The 2012 NRC report is the basis for updated sea-level rise guidance to state agencies. The Delta Plan cited anticipated sea level rise at the Golden Gate of 14 inches by 2050 and 55 to 65 inches by 2100 based on the interim guidance adopted by the Ocean Protection Council (OPC) in March 2011. In March 2013, OPC updated the guidance for state agency project planning based on the 2012 NRC report. The OPC noted that the purpose of the guidance is "to help state agencies incorporate future sea-level rise impacts into planning decisions." The agency further noted that the guidance "has now been updated to include the best current science, as summarized in the NRC report."[1] The California Coastal Commission also adopted these NRC sea level rise projections as the best available science (2015).

Table 1 Sea Level Rise Scenarios

Year	Average Estimate	High Estimate
Current	+2.0 inches (+5.0 cm)	Not analyzed
2030	+5.7 inches (+14.4 cm)	+11.7 inches (+29.7 cm)
2050	+11.0 inches (+28.0 cm)	+23.9 inches (+60.8 cm)

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[1] State of California Sea-Level Rise Guidance Document and Staff Report (2013), http://www.opc.ca.gov/2009/12/climate-change/, accessed August 14, 2015.

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The DLIS team developed Stage-recurrence curves for all Delta and Suisun Marsh islands and tracts; two of which are shown in Figure 1. The solid lines are stage-recurrence curves for present day sea level and were developed using the method shown in Attachment A. The dashed lines are for an average estimated sea level in 2050 (+11.0 inches from 2000 baseline) and were developed by adding the estimated sea level rise calculated by the method shown in Attachment B to the present day recurrence water elevations
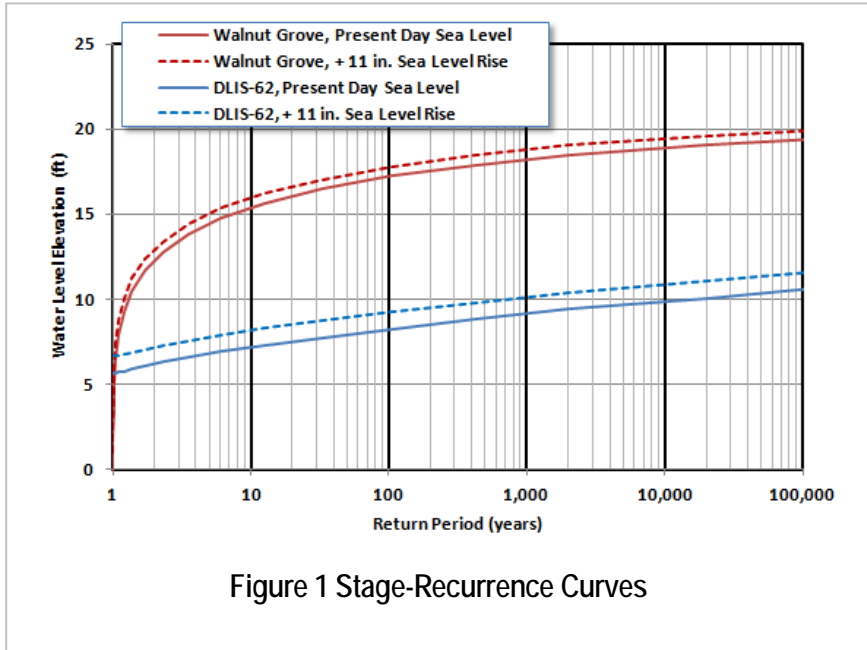

Figure 1 Stage-Recurrence Curves

(solid lines). In general, the effect of sea level rise (increase in water surface elevation) decreases with i) higher inflow to the Delta and Suisun Marsh; with ii) distance from the point of known sea level rise; and with iii) the difference between water level at the point of interest and water level at the point of known sea level rise. Hence, potential future sea level rise will have the greatest effect on the Suisun Marsh and western Delta islands and tracts.

Because the increment of water level change due to sea level rise depends on distance, inflow, (which is heavily regulated) and other variables, the DLIS team has not prepared a contour plot of the influence of the projected Delta and Suisun Marsh increases. However, the general pattern of water level increases due to sea level rise will be similar to the pattern of tidal effects shown in Figure 3 in the following section.

Stage-recurrence curves are combined with levee fragility curves to compute probabilities of levee failure at each water level and compute an annual probability of levee failure by integrating the two curves over all water levels. The implication of this integration is that, even if a levee fragility curve does not change with time, the annual probability of levee failure can increase because of sea level rise alone. The incremental probabilities of levee failure at each water level and the annual probability of levee failure are used in the calculation of expected annual fatalities, expected annual damage, and other metrics used in the DLIS planning tool ranking and prioritization algorithms.

3 Spatial Variation of Tide Effects in the Delta and Suisun Marsh

The tide cycle creates daily and seasonal variations in the Delta and Suisun Marsh water levels that, to varying degrees, mimic the daily and seasonal tide cycles at Golden Gate. The degree to which Delta and Suisun Marsh water levels mimic Golden Gate tide cycles depends on location within the Delta or Suisun Marsh. Water levels at islands and tracts in Suisun Marsh and the western Delta islands, near relatively large bodies of open water, have daily and seasonal variations that are essentially equal to local tide cycles. Water level cycles at islands and tracts farther inland and upstream of the open bodies of water are muted in approximate proportion to their distance from an open body of water.

In the DRMS study (DWR 2009), a simplified model of channel hydraulic characteristics and multiple regression methods were used to develop equations that relate Delta inflow and tide level to water level at 15 gauging stations in the Delta. Among the regression coefficients in this analysis is a tide factor that defines the effect of tide level at Golden Gate on water level at each gauging station. For example, a tide level of 5 feet at Golden Gate would contribute 4.55 feet (5 x 0.91) to the water level at the Sacramento River at the Mallard Island (MAL) gauging station. The tide factors from the DRMS analysis are shown in Table 2 and locations of the gauging stations used in their analysis are shown in Figure 2.

A planar interpolation concept was used by the DLIS team to estimate tide factors for every Delta and Suisun Marsh island and tract. A

Table 2 Gauging Stations

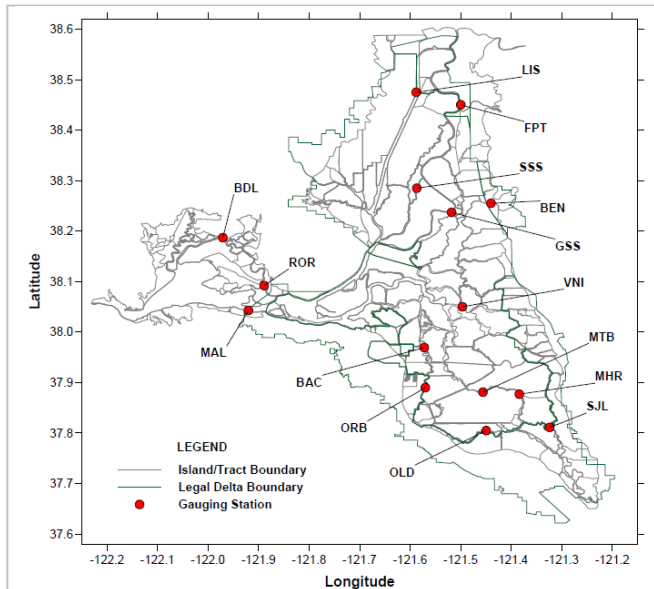| Gauging Station	Tide Factor
MAL Sacramento River at Mallard Island	0.91
BDL Beldon Landing	1.00
ROR Roaring River	0.94
BEN Benson's Ferry	0.38
GSS Georgiana Slough at Sacramento River	0.34
FPT Sacramento River at Freeport	0.00
SSS Steamboat Slough	0.19
LIS Yolo Bypass at Lisbon	0.67
MHR Middle River at Howard Road Bridge	0.88
MTB Middle River at Tracy Blvd.	0.90
OLD Old River near Tracy	0.81
BAC Bacon Island at Old River	1.00
ORB Old River at Byron	0.79
SJL San Joaquin River near Lathrop	0.77
VNI Venice Island	0.97

Figure 2 Gauging Stations
(Source: DWR 2009)

contour map generated by the DLIS team that shows the general distribution of the estimated tide factors is presented on Figure 3. The contours were developed from the individual island and tract tide factors and provide a general indication of the influence of tide throughout the Delta and Suisun Marsh.

As noted in the previous section, the distribution of sea level change effects in the Delta and Suisun Marsh will follow a pattern similar to that shown in Figure 3. The increase in water level at any location in the Delta and Suisun Marsh due to an increase in mean sea level at Golden Gate will be approximately equal to mean sea level increase near Carquinez Strait multiplied by the value shown on the contour map at that location. For example, a mean sea level rise of one foot at Golden Gate would create a water level rise of 0.2 to 0.3 feet at Walnut Grove. Similar calculations are performed for all islands and tracts for the DLIS analyses of 2030 and 2050 conditions.
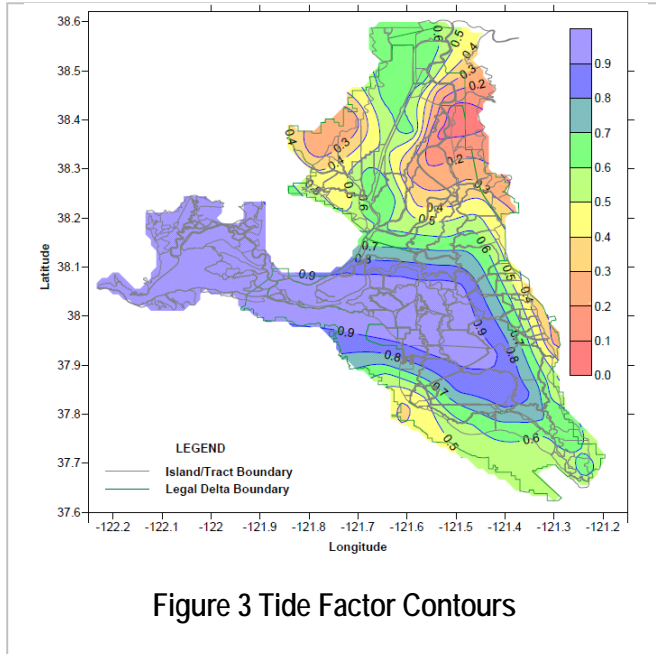

Figure 3 Tide Factor Contours

4   Sea Level and Water Level Prediction Uncertainties

The prediction of future water levels in the Delta and Suisun Marsh based on potential sea level rise at Golden Gate has several sources of uncertainty including: uncertainty in the predicting future sea levels at Golden Gate, uncertainty in predicting the hydrodynamic effects between Golden Gate and the Delta and Suisun Marsh, and uncertainty in predicting the hydrodynamic and hydraulic changes in the Delta and Suisun Marsh.

The uncertainty in predicting future sea levels is illustrated in Figure 4. The predicted increase in sea level at 2100
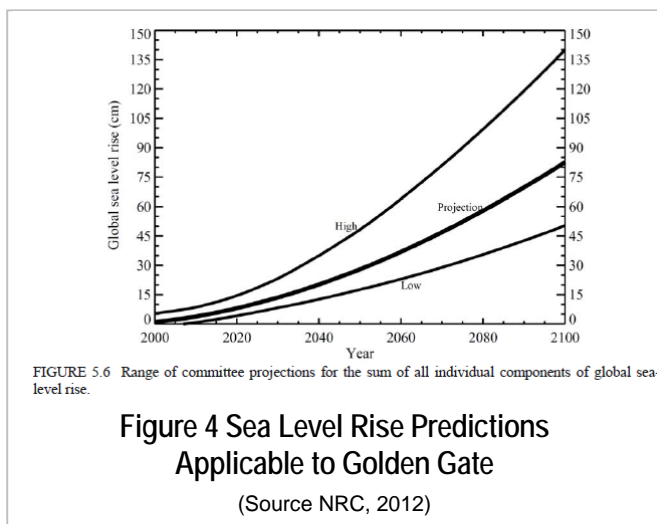

FIGURE 5.6 Range of committee projections for the sum of all individual components of global sea-level rise.

Figure 4 Sea Level Rise Predictions Applicable to Golden Gate
(Source NRC, 2012)

(NRC 2012) applicable to Golden Gate ranges from 50 to 140 cm (approximately 20 to 55 inches) with an average predicted rise of about 82 cm (approximately 32 inches). The uncertainties in sea level rise predictions for years 2030 and 2050 (DLIS analysis years) are less than in year 2100, but will contribute approximately 6 inches (year 2030) to 12 inches (year 2050) of uncertainty to the prediction of water levels in the Delta and Suisun Marsh.

A snapshot of the hydrodynamic effects between Golden Gate and the Delta and Suisun Marsh is shown in Figure 5. This graph shows the relationship between tide ranges at Golden Gate and at Martinez-Amorco Pier near the eastern end of Carquinez Strait. The plotted data are the differences between daily high-high and low-low tide levels for the months of December 2014 and June 2015. Total Delta inflows for December 2014 were above median December inflows, but well below flood stage. Total Delta inflows for June 2015 were only about 30% of median June inflows. While these data have a relatively high correlation coefficient ($r \geq 0.97$), flood-level inflows to the Delta and extreme tide levels at Golden Gate will introduce additional uncertainty into this relationship.

Figure 5 Carquinez Strait vs. Golden Gate Tide Range
(Source NOAA , 2015)
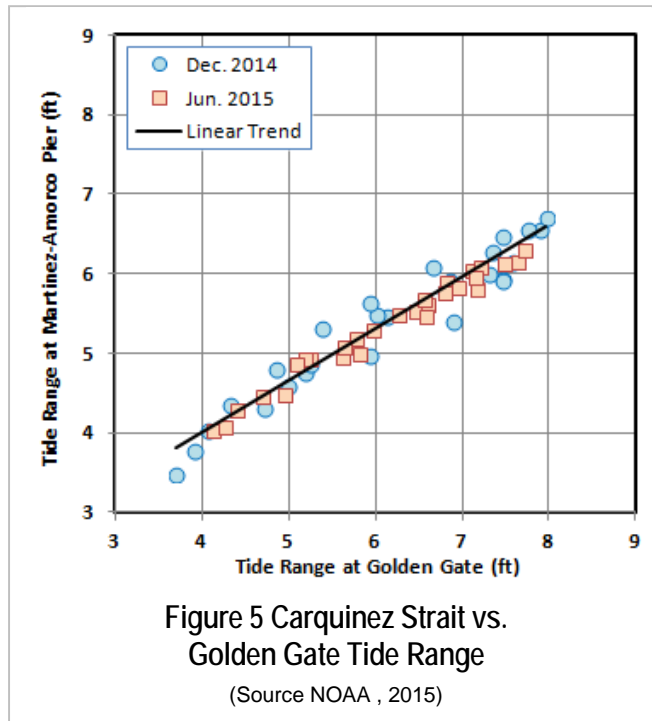
The key take-away from this graph is that the tide range in Carquinez Strait is 60 to 65% of the tide range at Golden Gate for the two months shown. While this small sample is not a definitive measure of the hydrodynamic effects between Golden Gate and the Delta and Suisun Marsh, it does illustrate the order of magnitude that the hydrodynamic effects will have on predictions of water levels in the Delta and Suisun Marsh.

It is also important to note that this relationship is only applicable to current sea level. Increases in average sea level at Golden Gate may alter the hydrodynamic effects between Golden Gate and the Delta and Suisun Marsh. Additional studies of the influence of sea level rise on the hydrodynamics of San Francisco Bay are underway by the San Francisco Bay Regional Coastal Hazards Adaptation Resiliency Group (CHARG, 2015) and the City of San Francisco (San Francisco, 2014). However, until their results are published, the DLIS team will continue use the method described in Attachment B to evaluate sea level rise effects on the prediction of water levels in the Delta and Suisun Marsh.

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Topical Area: Flood Hazard

5.5.2 Regression Analyses of Water-Surface Elevations

Using the data on maximum daily tide, mean daily inflow, and measured adjusted stages at the gauging stations, multiple regression analyses were made for each of the stage- measuring stations. The regression analyses were made to determine best fit coefficients for Equations 5-1 and 5-2. Either Equation 5-1 or 5-2 was used in the regression analyses, depending on the stage measuring station being analyzed. Equation 5-1 was used to estimate stages at the Freeport and Lisbon stations because stages at these stations depend on flow in Sacramento River and Yolo Bypass, respectively, and not the combined flows in Sacramento River and Yolo Bypass. Equation 5-2 was used for the other stage- measuring stations because the measured stage better correlates with the combined Sacramento River and Yolo Bypass flows.

$$WSE_i = aT + b(Q_{Sac})^{b'} + c(Q_{Yolo})^{c'} + d(Q_{SJ})^{d'} + e(Q_{Cos})^{e'} + f(Q_{Mok})^{f'} + g(Q_{misc})^{g'} \qquad (5\text{-}1)$$

$$WSE_i = aT + b(Q_{Sac}+Q_{Yolo})^{b'} + d(Q_{SJ})^{d'} + e(Q_{Cos})^{e'} + f(Q_{Mok})^{f'} + g(Q_{misc})^{g'} \qquad (5\text{-}2)$$

where:

WSE_i	= water-surface elevation at station "i"
T	= Golden Gate maximum daily tide elevation
Q_{Sac}	= Sacramento River inflow
Q_{Yolo}	= Yolo Bypass inflow
Q_{SJ}	= San Joaquin River inflow
Q_{Cos}	= Cosumnes River inflow
Q_{Mok}	= Mokelumne River inflow
Q_{misc}	= miscellaneous inflow

The theoretically derived weir equation and Manning's Equation for a simple river (e.g., cross-sectional area equal width times depth) indicate that discharge per unit width of flow (q) is proportional to the hydraulic head to the 1.5 power, or, conversely, the hydraulic head is proportional to discharge to the 0.67 power (Streeter and Wylie 1979). Thus, the b' through g' exponents in Equations 5-1 and 5-2 were set equal to 0.67. Coefficients "a" through "g" are determined from the regression analyses.

Each component of Equations 5-1 and 5-2 represents the contribution to the expected stage of tide and flow from each inflow source.

In the regression analyses, a condition was imposed on the "a" through "g" coefficients to restrict these coefficients to positive values. Negative values for these coefficients would indicate a decrease in stage for an increase in flow, which is not realistic.

Regression analyses were performed for the 15 stage-measuring stations listed in Table 5-3. The multiple linear regression analyses were solved in two steps. In the first regression, the average absolute error was minimized. In the second regression, the average error was minimized. The absolute average error ranged from 0.17 feet to 0.92 feet.

The coefficients "a" through "g" derived from the regression analyses are presented in Table 5-4. The resulting average absolute error and maximum error were determined and are also presented in Table 5-4.

5.6 Evaluation of Flood Stage Equations

At each station the measured water-surface elevation was compared to the water-surface elevation calculated using the coefficients listed in Table 5-4. Figure 5-5 compares the calculated stage with the measured stage at Venice Island for the period January 1998 to July 1998. Similar comparisons for the stations listed in Tables 5-2, 5-3, and 5-4 are provided in Appendix A. Also, the observed annual peak at each station is compared to the predicted annual peak for stations with four or more years of data. For most stations, the root mean square error is equal to 0.34 feet or less. Only two stations, Benson's Ferry and Liberty Island, have root mean square errors that are greater than 1 foot.

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Topical Area: Flood Hazard

5.7 Interpolation of Stages at Intermediate Locations

Given the coefficients "a" through "g", a stage elevation can be predicted at each of the selected stage-measuring stations (primary stations) for any inflow pattern and tide condition. Stage estimates are also needed at locations where measured data are not available. Critical locations were selected (e.g., stream junctions) (secondary stations), and the stage at these locations was estimated by linear interpolation of the distances along the primary Delta channel flow path between the primary locations that passed through the secondary station.

5.8 Assumptions and Limitations

These analyses assume a channel system within the Delta that is regular and that behaves consistently over the period since 1984, when stage data first became available. At least two artificial (human-made) conditions exist in the Delta waterways that may account for some of the error found in the equations.

The weir near the Lisbon station can be operated to release flows at different stage elevations on the Sacramento River. The relatively larger error for this station may partly result from water releases made at different stage elevations over the past 22 years. For example, operators may choose to begin to release water at a lower-than-usual stage to minimize the danger to urban areas from higher flows expected in the near future. These operational issues have not been explored in these analyses.

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Topical Area: Flood Hazard

6.5 Future Delta Water-Surface Elevations

Water-surface elevations in the Delta will change in the future due to rising sea levels. The increases in sea level cannot simply be added to the water-surface elevations estimated as described in Section 5; the sea-level rise will change the hydraulic characteristics of flows through the Delta and its impact should decrease the farther inland a location is and the larger the storm event. A simple method to approximate changes in water-surface elevations in the Delta due to sea-level rise was developed and is described in the following paragraphs.

A rise in sea level increases the tailwater that inflows must overcome to pass through the Delta and enter San Francisco Bay. For any given inflow magnitude and pattern flow, depths in the Delta channels will be larger, thereby reducing flow velocities and hydraulic head losses. The reduction in hydraulic head loss must be accounted for in estimating water-surface elevations under future increased sea-level conditions. The following assumptions were made in analyzing impacts of sea-level rise on water-surface elevations in the Delta:

1. Manning's Equation can be used to describe the flow in the Delta channels during storm events.

2. The channels are much wider than they are deep; therefore, the hydraulic radius can be approximated as the channel depth.

3. The slope of the channel can be approximated as the water-surface slope between the station of interest and the next downstream station.

4. The water-surface elevation at any station can be approximated using the relationships developed in Section 5.

Using the above assumptions, the sea-level rise at any location in the Delta can be estimated using Equation 6-1.

$$\left(\frac{h_B}{h_B + d_B}\right)^{5/3} = 1 + \frac{d_B - d_A}{f_B(Q_i) - f_A(Q_i)} \tag{6-1}$$

where:

h_B = water depth at location of interest

d_B = sea-level rise at point of interest

d_A = known sea-level rise at downstream point

$f_B(Q_i)$ = water-surface elevation at point of interest calculated from relationships in Section 5

$f_A(Q_i)$ = water-surface elevation at point downstream calculated from relationships in Section 5

Equation 6-1 is applied starting from the farthest downstream point (e.g., the Mallard Island station) and moving upstream.

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