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Streambed-scour monitoring at selected bridge sites in Alaska is being used to assess real-time hazards, but also illustrates the complexities of streambed scour and the difficulty of predicting scour using existing methods. Four years of stage and bed-elevation data at the Knik River near Palmer, Alaska show an annual cycle of channel aggradation and degradation to an equilibrium level that is punctuated by shorter periods of scour and fill. The annual vertical bed-elevation change exceeds 6 meters and is an interplay of sediment supply, discharge, and the influence of instream hydraulic structures. Channel contraction at this site is nearly four to one at high flows and upstream guide banks direct flow through the bridge reach.

Data from a pier-mounted sonar together with hydraulic variables measured during high flows and variables computed with a multi-dimensional hydrodynamic model were used to evaluate seven predictive equations for live-bed contraction scour and two abutment scour computations. Two scour events were simulated with the hydrodynamic model; one related to rainfall, the other owing to a period of increased glacial melting. Streambed scour for these two events varied considerably in timing and duration although both had similar streamflow discharges. Total computed scour exceeded measured values by 40 to 60 percent depending on the equations selected. The long-term monitoring data indicate the scour at this site is not only a reaction to changes in hydraulic variables, but is also affected by the timing and duration of streamflow as well as the source of the high flow, factors not typically included in the engineering assessment of streambed scour.

I. INTRODUCTION

Streambed scour followed by fill after a flood passage is a well documented process at locations where regular cross-section measurements are made. Data describing the timing and duration of this process are limited by the frequency of field visits. To better understand this process and to monitor bed elevation at bridge piers, the U.S. Geological Survey and the Alaska Department of Transportation and Public Facilities operate a network of streambed scour-monitoring stations in Alaska. Currently 16 bridges are instrumented with sonars to measure distance to streambed and river stage. These stations provide state engineers with near real-time bed elevation data to remotely assess scour at bridge piers during high flows. The data also provide a nearly continuous record of bed elevation in response to changes in discharge and sediment supply. Seasonal changes as well as shorter duration scour and fill have been recorded. In addition to the near real-time data, channel bathymetry and velocity profiles are collected at each site several times per year. This paper focuses on 4 years of hydraulic and sonar data collected at the Knik River. These data are compared to results from predictive scour calculations using variables generated by a hydrodynamic model.

There are two bridges that cross the Knik River on the Old Glenn Highway (Fig. 1). The upstream most bridge, which is no longer open to vehicular traffic, is 610 m long and is supported by six piers. Approximately 30 m downstream of this structure is the active bridge that was built in 1975 and is 154 m in length and supported by two piers. The roadway approaches to this bridge significantly contract the channel. Two guide banks extend upstream of both bridges and route flow through the rip-rap lined bridge reach. All piers are approximately aligned with the flow.

The right-bank pier of the new bridge was instrumented with a retractable, pier-mounted 235 kilohertz echosounder in 2002. Stage data were measured by a U.S. Geological Survey stream gage (Station number 15281000). The echosounder was mounted at an angle on the side of pier near the nose in order to collect data just upstream of the pier footing and subfooting. Data are collected every 30 minutes and transmitted every 6 hours. When bed elevation or stage thresholds are exceeded, data transmissions increase in frequency. These near real-time data for the Knik River and other sites in Alaska are available on the web at http://ak.water.usgs.gov/usgs_scour. Streambed elevation and stage data accuracies are ±0.15 m and ±0.03 m, respectively. All elevations reported here are referenced to the North American Vertical Datum of 1988.

II. STREAMBED SCOUR AT THE KNIK RIVER

The Knik River near Palmer was the only site within the monitoring network that had large changes in bed elevation each year. Annual scour ranged from 5.2 m to 6.0 m. The Knik River is a braided sand and gravel channel that transports large quantities of sediment from the Knik Glacier. The braided channel narrows from approximately 4.8 km wide at the glacier mouth to 0.12

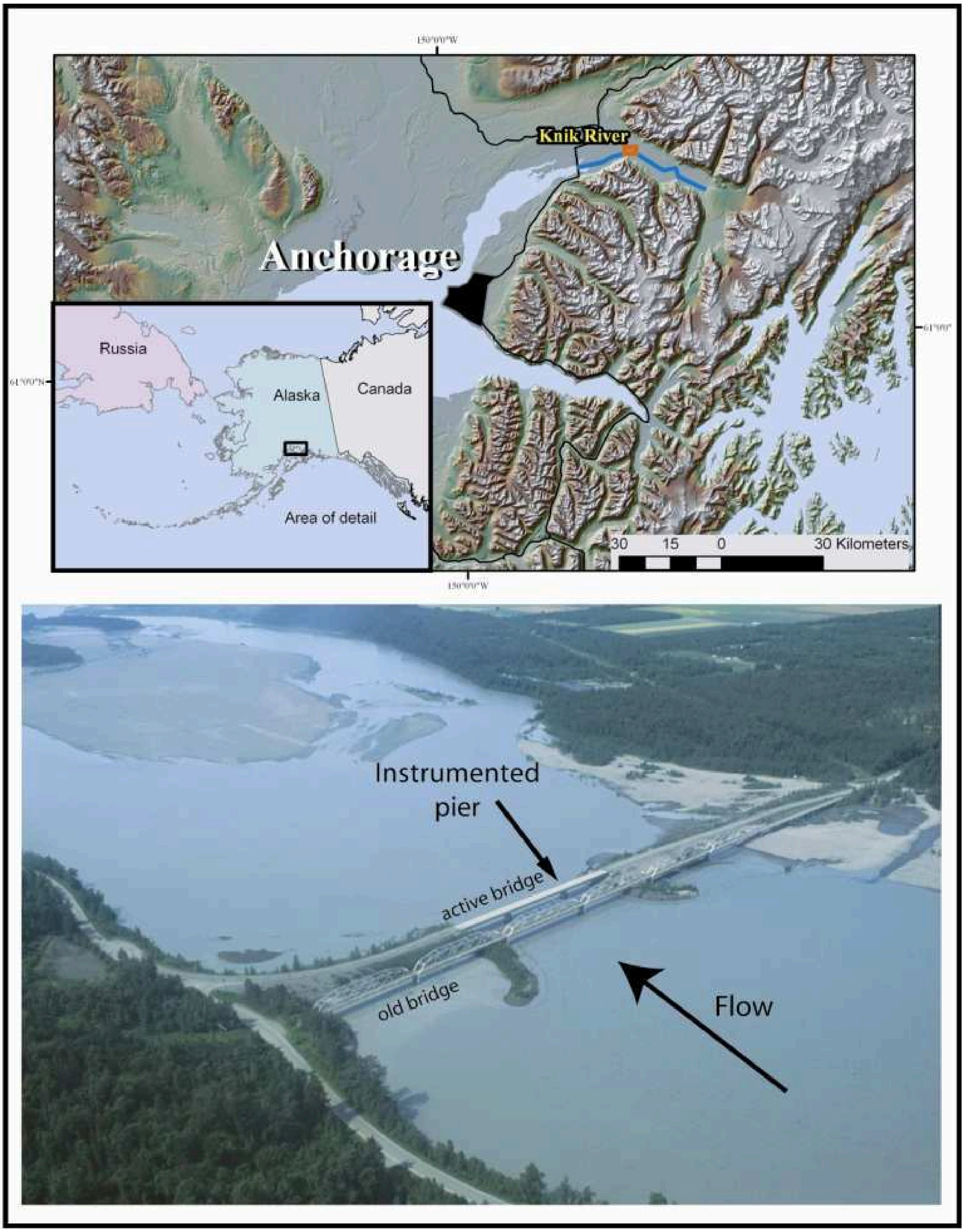

Figure 1. Location of the Knik River Old Glenn Highway bridge and oblique aerial photo of the study reach during a summer high flow.

km at the Old Glenn Highway bridge where the channel is subject to a 4:1 contraction during summer high flows. It drains an area of approximately 3,100 km^2, over half of which consists of glaciers. At a discharge of 850 m^3/s on July 12, 2003, suspended sediment-concentration was measured at 711 mg/L and bedload discharge was 8,160 metric tons/d. Median grain size of the bedload was 2.0 mm. Scour at this site is a complex interaction of seasonal bed elevation changes, flow hydraulics associated with upstream guide banks, and bed armoring associated with the complex pier shape. The current morphological and alluvial characteristics of the river can be partially attributed to large glacial-outburst floods that occurred nearly every year from 1914-1966. The maximum measured discharge from these events was 10,200 m^3/s.

These outburst floods no longer occur because of recession and thinning of the Knik Glacier.

Streambed scour at the Knik River was initially investigated by Norman [1]. His study focused on data collected in 1965 and included measurements made during a glacial outburst flood with a discharge of 6,680 m^3/s. At this time only the upstream bridge was present and there was no significant channel contraction. Reference [1] measured no appreciable contraction scour and 1.15 m of local pier scour.

A. *Discussion of Monitoring Data*

Since the installation of the monitoring equipment, discharge at the Knik River has ranged from 17 m^3/s to 1,710 m^3/s for water years 2002-2005. During the winter months, the streambed at the monitored bridge pier aggraded to an elevation of between 9.8 and 10.4 m each year (Fig. 2). From the beginning of data collection each year in early May until the latter part of June, the bed degraded at an average rate of 0.06 m/day, about 2.4 m each year. Over this same period of time, the stage increased at a rate of 0.02 m/day, 0.03 m/day, and 0.02 m/day for 2003, 2004, and 2005, respectively. Following this period of seasonal channel degradation the bed elevation at the pier remains relatively stable at an elevation of 7.8 m (equilibrium elevation), with brief periods of scour and fill during high flows. The channel begins to aggrade each year in September as stage decreases.

The mean bed elevation at a river cross section is not only dependent upon discharge, but is also related to changes in width, depth, velocity, and sediment load during the passage of a flood [2]. Streambed scour in the bridge reach is an interplay of discharge, sediment transport and the flow hydraulics associated with the channel contraction, upstream guide banks, and piers. Although the sonar only measures the bed elevation in front of the right-bank pier, the measured changes in bed elevation represent channel change from all the above factors. The cross section defined by the upstream bridge opening was surveyed periodically to document changes in bed elevation across the channel (Fig. 3). These cross sections and the sonar data show an annual cycle in channel change. Scour at this site is not uniformly distributed across the channel and is a combination of live-bed contraction and abutment scour along the guide banks. Vortices that develop as flow is routed around the guide banks erode the right and left portions of the channel and there is little bed-elevation change in the middle except at high flows. Increases in stage result in larger flow vortices and progressive deepening of the channel from the banks towards the center of the channel.

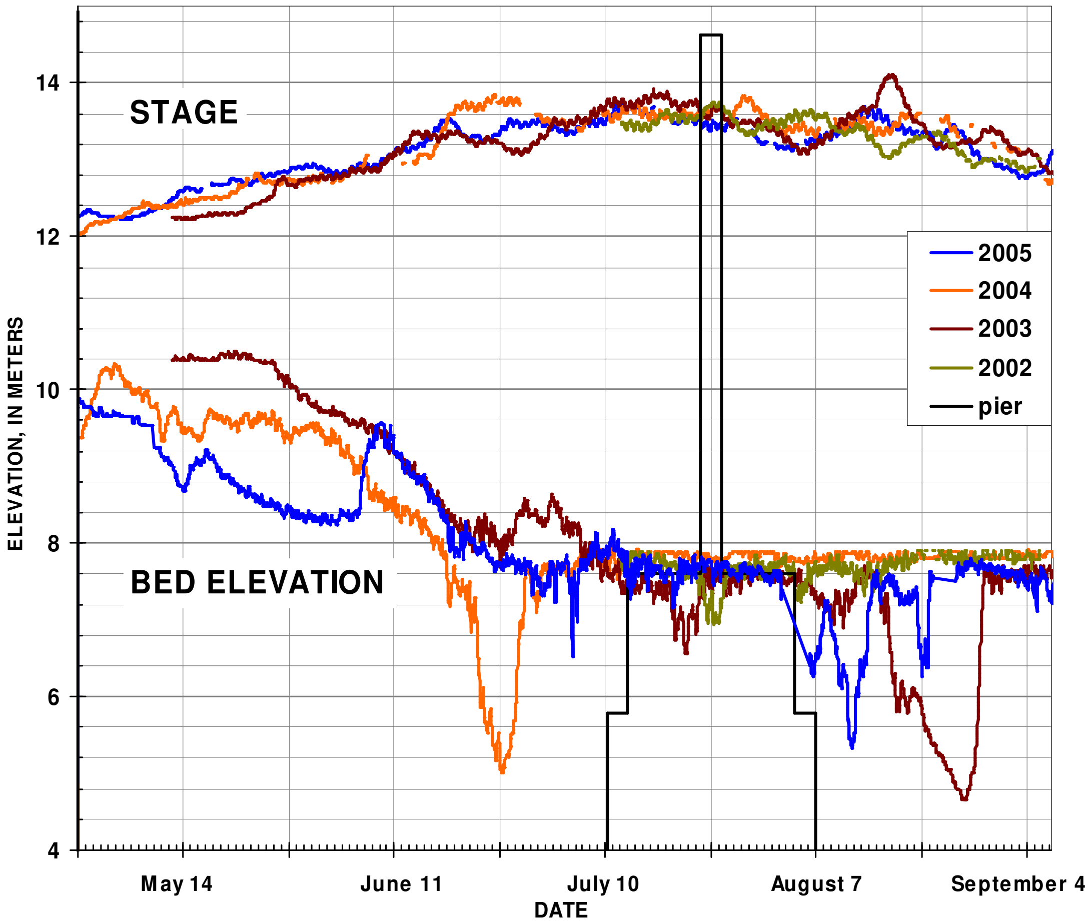

Figure 2. Stage and bed elevation at the monitored bridge pier for 2002-2005 at the Knik River near Palmer, Alaska. The bridge pier and footings are plotted for reference.

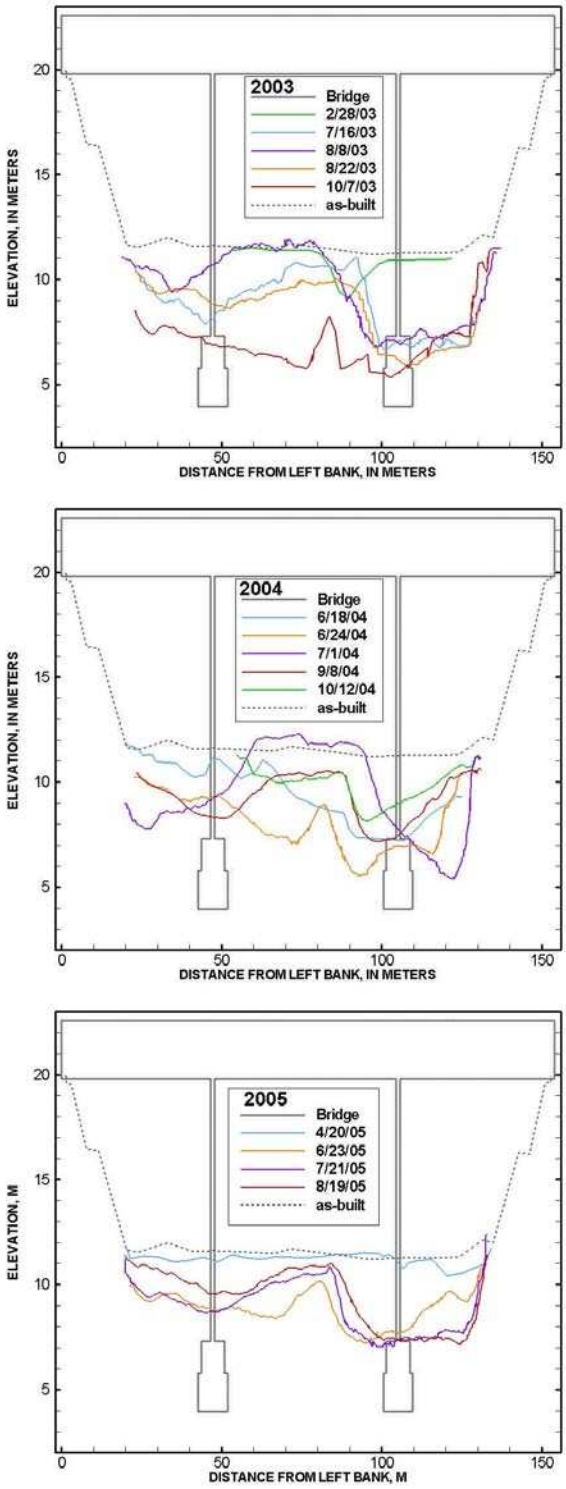

Figure 3. Upstream bridge cross sections at the Knik River for 2003-2005.

At higher stages, this scour along the channel margin overrides the effects of local scour at the pier where the sonar is mounted. The pier is supported by a 7.3 m wide footing and 9.1 m wide sub footing. These footings appear to armor the local bed and bed elevation remained near the elevation of the top of the footing for extended periods (Fig. 2). These observations agree with those of Parola et al. [3], who found that rectangular pier footings protect the streambed from the scouring of vortex systems formed by the pier until the streambed is below the footing then vortices from the footing induce scour. Local scour at the right-bank pier was not distinguishable from the contraction and abutment scour in surveyed bridge cross sections (Fig. 3). A depression in the cross section at the pier would indicate local scour.

The channel at the Knik River scours vertically and laterally towards the center to accommodate increased summer discharge. Vertical and lateral scour are concurrent until the footing of the pier is reached, at which point vertical scour is limited and increases in channel area are made by lateral scour. This process is illustrated in the successive cross sections plotted in Fig. 3. The lateral scour then proceeds until the channel width intersects vortices that are shed from a pier supporting the upstream bridge. These vortices weaken downstream of the old bridge pier and deposit sediment that was scoured locally from the upstream pier. A bar that formed downstream of the pier is visible in the middle of the channel in soundings from 2003 and 2004 (Fig. 3).

Two distinct scour and fill events from 2003 and 2004 highlight differences in timing and duration of scour (Fig. 4). Both scour events were associated with a period of high temperatures and subsequent increased glacial melt, but in 2003 the warm weather was followed by 10 days of rainfall and cooler temperatures. Scour magnitude for both events was approximately 3 m from the equilibrium bed elevation. The maximum scour occurred slightly after the peak in stage in 2003 and in 2004 maximum scour was concurrent with peak stage. The duration of scour, measured from when the bed elevation begins to decrease until fill begins, was 11.5 days in 2003 and 4 days in 2004. The scour in 2003 was of greater duration because the discharge and sediment supply from the glacier was reduced by the cooler temperatures. The channel infilled 3 m in 2 days after warmer temperatures resumed, likely accompanied by an increase in sediment load. In 2004, stage increased rapidly prior to scour and was then steady with diurnal fluctuations. The scour began after the bed had degraded to the elevation of the top of the pier footing. Filling of the channel began before the stage began to decrease. Since bed elevation changes in alluvial systems are the response to changes in sediment supply and flow hydraulics, and flow hydraulics were relatively constant during this event, an increase in sediment supply from the glacial melt water is thought to have initiated the filling.

III. Hydrodynamic Modeling

The U.S. Geological Survey's Multi-Dimensional Surface Water Modeling System (MD_SWMS) [4] was selected to simulate hydraulic conditions for the 2003 and 2004 scour events. MD_SWMS is a pre- and post-processing application for computational models of surface-water hydraulics. MD_SWMS uses a multi-dimensional steady-state model of flow, FaSTMECH [5].

The model was calibrated to surveyed water-surface elevations and two-dimensional velocity vectors

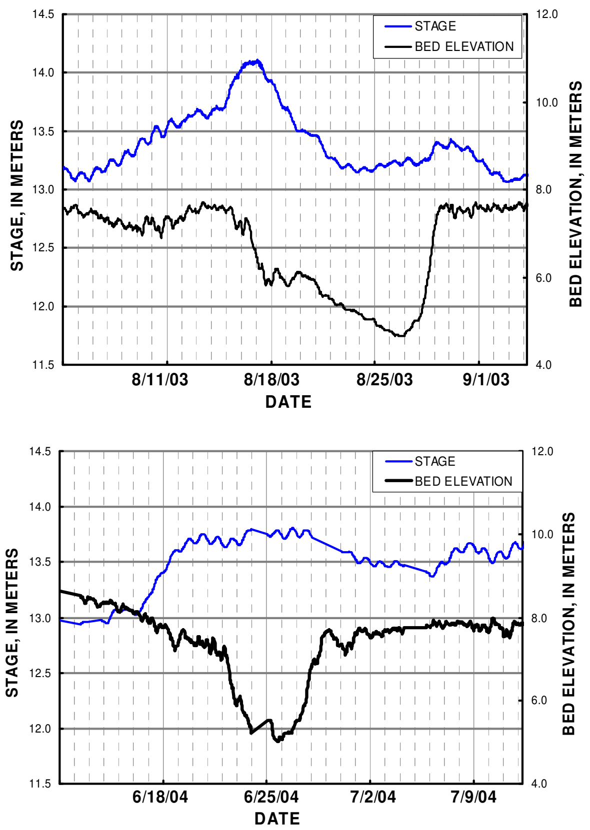

Figure 4. Stage and bed elevation at monitored bridge pier from two scour and fill events on the Knik River near Palmer, Alaska. Stage increases were the result of rainfall (2003, upper plot) and glacial melting from a prolonged period of warm weather (2004, lower plot).

measured with an acoustic Doppler current profiler. The peak discharge for each scour event was then simulated with the calibrated model. Hydraulic variables needed for the computation of predictive contraction and abutment scour were extracted from model results and are discussed below. A multi-dimensional model was required to properly simulate the flow routing around the guide banks and to accurately determine the area of active flow that was obstructed by the embankments.

IV. Computation of Scour

Total scour at the Knik River is a combination of scour at the piers, abutment scour along the guide banks, and contraction scour. Separating the individual components of scour from the monitoring and field data is difficult. Local scour at the bridge piers was not observed in cross section bathymetry at high flows and was not included in the computation of total scour. The contraction scour component was separated from the abutment scour along the guide banks by measuring the bed elevation change in the center of the channel. For this assessment, scour along the right and left banks is considered purely abutment scour. Actual conditions are likely a combination of all three components.

A. Contraction Scour

Contraction and abutment scour at the Knik River are considered live-bed. Under live-bed conditions, contraction scour in the bridge section reaches a minimum when sediment transport into the contracted section equals sediment transport out or when the mean velocity equals the critical velocity of the mean-diameter bed material. An equilibrium is reached when the transport capacity in the contracted section decreases because of increasing channel area and the attendant decrease in flow velocity. The banks of the river in the bridge reach are armored with rip-rap, so increases in channel area occur through a combination of vertical scour and lateral scour towards the center of the channel. Contraction scour does not occur uniformly across the channel (Fig 3.). There are two active areas of scour along the right and left banks through the bridge.

Predictive contraction-scour equations do not directly compute the depth of scour, but rather the depth of flow in the contracted section for equilibrium conditions. The most widely used equations are semi-empirical and based on formulas of sediment transport and uniform flow. The equations evaluated here all incorporate flow depths and ratios of discharge and channel width in the contracted and uncontracted sections. At this site, the volume of flow in the active channel in the approach is always equal to the flow through the bridge. The discharge ratio factor is therefore not needed and the common form of the contraction scour equation is simplified to:

$$y_{CS} = y_1 \left(\frac{w_1}{w_2} \right)^{Ew} - y_1 \qquad (1)$$

where,

y_{CS}	is scour depth in the contracted section, in meters;
y_1	is the average depth in the upstream main channel, in meters;
w_1	is the width of the main-channel of the approach section, in meters;
w_2	is the width of the of the main-channel in the contracted section, in meters; and
E_w	is a coefficient that accounts for the method of sediment transport. Values are presented in Table 1.

The estimated contraction-scour depth is the difference between the flow depth in the contracted section after scour has occurred and the flow depth that existed prior to any scour. Estimation of the flow depth prior to scour is difficult. The channel geometry in the contracted section, when the channel bathymetry was collected for the hydrodynamic model, had already been modified to some degree by abutment and contraction scour. A reference surface from which the total scour can be subtracted must be established. This surface typically is determined either from the channel geometry of the upstream uncontracted section or by interpreting a surface along a longitudinal profile that spans the contracted section. The monitoring data show that the bed aggrades annually to an average elevation of 10.1 m during the lower winter discharges when there is no contraction of the channel. This elevation also agrees with the elevation determined using the longitudinal profile method.

Live-bed contraction scour was estimated for the 2003 and 2004 scour events using several predictive equations. The equations are all similar in form to (1), but use different sediment-transport exponents (E_w) that are

TABLE I. CONTRACTION SCOUR VARIABLES AND COMPUTED SCOUR

Variables		2004	2003
Q	Discharge	934 m^3/s	1180 m^3/s
w_1	Width of approach section	450 m	450 m
w_2	Width of contracted section	120 m	120 m
y_1	Average depth of approach section	1.9 m	2.2 m
y_s	Observed scour depth	2.7 m	2.9 m

Sediment Transport Coefficients (E_w)		Computed Scour (y_s)	
Laursen [6]	0.59	2.2 m	2.5 m
Straub [7]	0.43	1.5 m	1.6 m
Straub [7]	0.642	2.5 m	2.9 m
Komura [8]	0.85	3.9 m	4.5 m
Komura [8]	0.667	2.7 m	3.0 m
Culbertson et al. [9]	0.667	2.7 m	3.0 m
Griffith [10]	0.637	2.5 m	2.8 m

summarized in Table 1 along with the computed scour values. The values range from 1.5-3.9 m and 1.6-4.5 m for the 2004 and 2003 scour events. Measured scour in the center of the channel from the reference elevation was 2.7 m in 2004 and 2.9 m in 2003.

B. *Abutment Scour*

Abutment scour is dependent upon the amount of flow obstructed by the abutment, shape and alignment of the abutment, sediment characteristics, and flow hydraulics. The guide banks that extend upstream of the bridge were designed to route flow through the contracted bridge reach. As flow is routed around the guide banks into the bridge reach horizontal vortices develop at the nose and scour the channel along two zones adjacent to each abutment (Fig. 5). The guide banks and abutments themselves are all lined with riprap and protected from scour. As discharge increases, more flow is routed around the guide banks and the magnitude of the vortices and depth of scour increases until an equilibrium is reached for the flow conditions. Scour is greater along the right bank because more flow is conveyed on this side of the channel. Abutment scour was estimated for the right bank only.

The two recommended equations in the Hydrologic Engineering Circular 18 [11] are based predominately on laboratory data. Froehlich [12] developed the following equation from a regression analysis of laboratory flume data:

$$y_s = y_f \left[2.27 K_1 K_2 \left(\frac{L'}{y_f} \right)^{0.43} Fr^{0.61} + 1 \right] \quad (2)$$

where,

y_s is scour depth at the abutment, in meters;

y_f is the average depth of flow on the flood plain, in meters;

K_1 is a coefficient for abutment shape;

K_2 is a coefficient for angle of abutment to flow;

L' is the length of active flow obstructed by the embankment, in meters, and

Fr is the Froude number of the approach flow upstream of the abutment.

The second recommended equation is based on field data collected on spur dikes on the Mississippi and is applicable when the ratio of the projected abutment length to the flow depth is greater than 25, a condition that is satisfied for the Knik River. This equation is referred to as the HIRE (Highways in the River Environment) [13] equation:

$$y_s = y_f \left(4 Fr^{0.33} \frac{K_1}{0.55} K_2 \right) \quad (3)$$

where,

y_s is scour depth at the abutment, in meters;

y_f is the average depth of flow on the flood plain, in meters;

K_1 is a coefficient for abutment shape;

K_2 is a coefficient for angle of abutment to flow, and

Fr is the Froude number of the approach flow upstream of the abutment.

In both equations, the area defined as flood plain was the area of the channel between the nose of the guide bank and the right bank shoreline. These equations typically result in overly conservative estimates of scour because they were developed using the abutment and roadway approach length as one of the variables. At this site, the discharge intercepted by the abutment is a function of stage not abutment length. Sturm [14] addressed this concern by evaluating the discharge intercepted by the abutment rather than length of the abutment, but his equations were developed for clear-water scour and extension to live-bed conditions is tentative. The variables and computed scour results from (2) and (3) are summarized in Table 2.

TABLE II. ABUTMENT SCOUR VARIABLES AND COMPUTED SCOUR.

Variables		2004	2003
Q	Discharge	934 m^3/s	1180 m^3/s
y_f	Average depth of flow on the floodplain	3 m	3.2 m
K_1	Spill through abutment shape coefficient	0.55	0.55
K_2	Coefficient for 90 degree angle of abutment into flow	1	1
Fr	Froude number of approach flow	0.22	0.26

Abutment Scour Equation	Computed Scour (y_s)	
Froehlich [12]	7.6 m	8.4 m
HIRE [13]	7.3 m	8.2 m

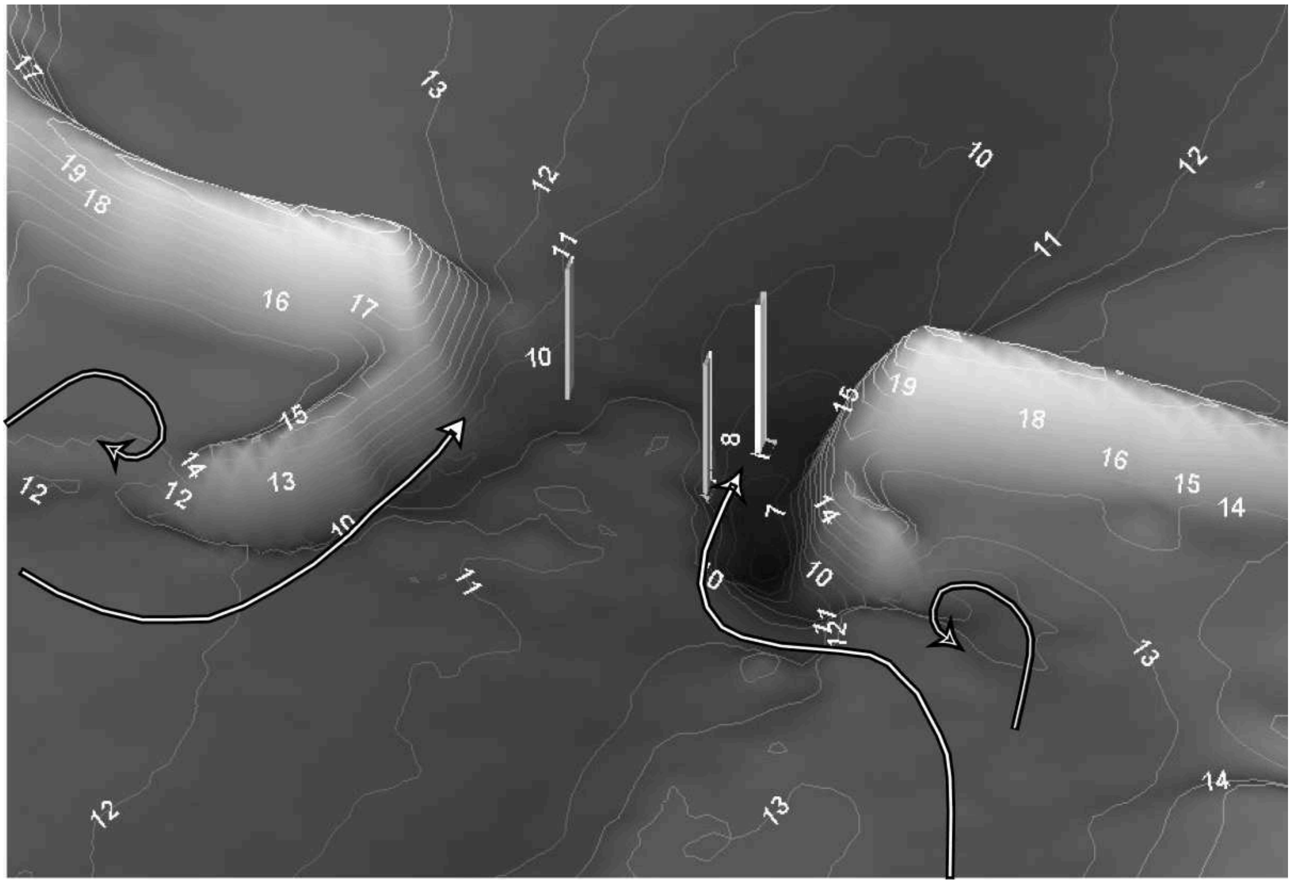

Figure 5. Topography and bathymetry at the Knik River with approximate lines of flow. Contours elevations are in meters, North American Vertical Datum of 1988.

The total measured scour at the right-bank pier as measured from the reference surface elevation of 10.1 m for the 2003 and 2004 scour events was 5.3 m and 5.1 m, respectively. The results from (2) and (3) overestimated scour for the 2003 event by 55 percent and 60 percent, respectively. The results from (2) and (3) for the 2004 scour event overestimated scour by 43 percent and 50 percent respectively. This overestimation would be greater if the estimated contraction scour were included for the right side of the channel.

V. Summary

Long-term streambed-scour monitoring data from a bridge pier on the Knik River illustrate an annual pattern of channel aggradation and degradation that is punctuated by shorter periods of scour and fill. Observed scour over 4 years of study averaged 6 m. Scour at this site is complex and is a combination of pier, contraction, and abutment scour, with abutment scour being the primary factor. The duration and magnitude of streambed scour was dependent on the source and timing of high flows. Two scour events with similar discharges were modeled with a multi-dimensional hydrodynamic model and results were used to calculate contraction and abutment scour with recommended predictive equations. Computed contraction scour over and under calculated the scour that was observed. The computed abutment scour over estimated by 43 to 60 percent. Pier scour was not computed because it was not observed at high flows.

Long-term monitoring data are necessary to distinguish seasonal scour from short-term scour and to determine the components of scour and their individual influence. The over prediction of computed abutment scour illustrates the need for further refinement of these equations for live-bed conditions. Data collected at this site will contribute to the need for field data at sites with significant abutment scour.

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