Hubbard Glacier, Russell Fiord and Situk River – A Landscape in Motion

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Hubbard Glacier, Russell Fiord and the Situk River near Yakutat, Alaska are glacial terrains and forelands in a constant state of motion. The area is an extremely active and dynamic landscape with an advancing tidewater glacier (10 km wide at tidewater), two major seismic faults, and a maximum net isostatic uplift rate of 0.44 cm/yr. The southern end of Russell Fiord is confined by a terminal moraine whereas the northern end of the fiord flows into Yakutat Bay. In 1986 and 2002, the advance of the Hubbard Glacier blocked the northern of the Russell Fiord from Yakutat Bay, temporarily creating Russell Lake. Subsequent failure of the ice or moraine dams in 1986 and 2002, respectively, produced the two largest glacial outburst floods in historic times. Both of these dams failed before the lake had risen to an elevation that would have caused it to spill over the terminal moraine at the southern end of Russell Fiord into the Situk River drainage. In 2002 the Tongass National Forest commissioned an interagency technical team to investigate the implications of the Hubbard Glacier completely closing Russell Fiord and rising lake levels overtopping the moraine at the southern end of Russell Fiord, forcing flow into the historic Situk River channel. Complete closure of Russell Fiord has major economic and safety issues affecting the City of Yakutat. The Situk River provides world class sport, subsistence and commercial fishing, which drives and supports the majority of the Yakutat economy. A sustained closure of the Hubbard-Russell ice dam will increase average daily flows in the Situk River from the current 3 to 11 cubic meters per second (cms) to over 566 cms if Lake Russell overtops the moraine, resulting in significant short and long-term changes to the river ecosystem. Hydrologic and geomorphic analyses of potential overflow scenarios were performed using data obtained from field and remote sensing technologies. The results and methods used to perform the analyses are discussed.

Keywords: *glaciers, LIDAR, flood modeling, geophysical survey, floods, ice dam stability, jokulhlaups, glacial outburst floods*

Introduction

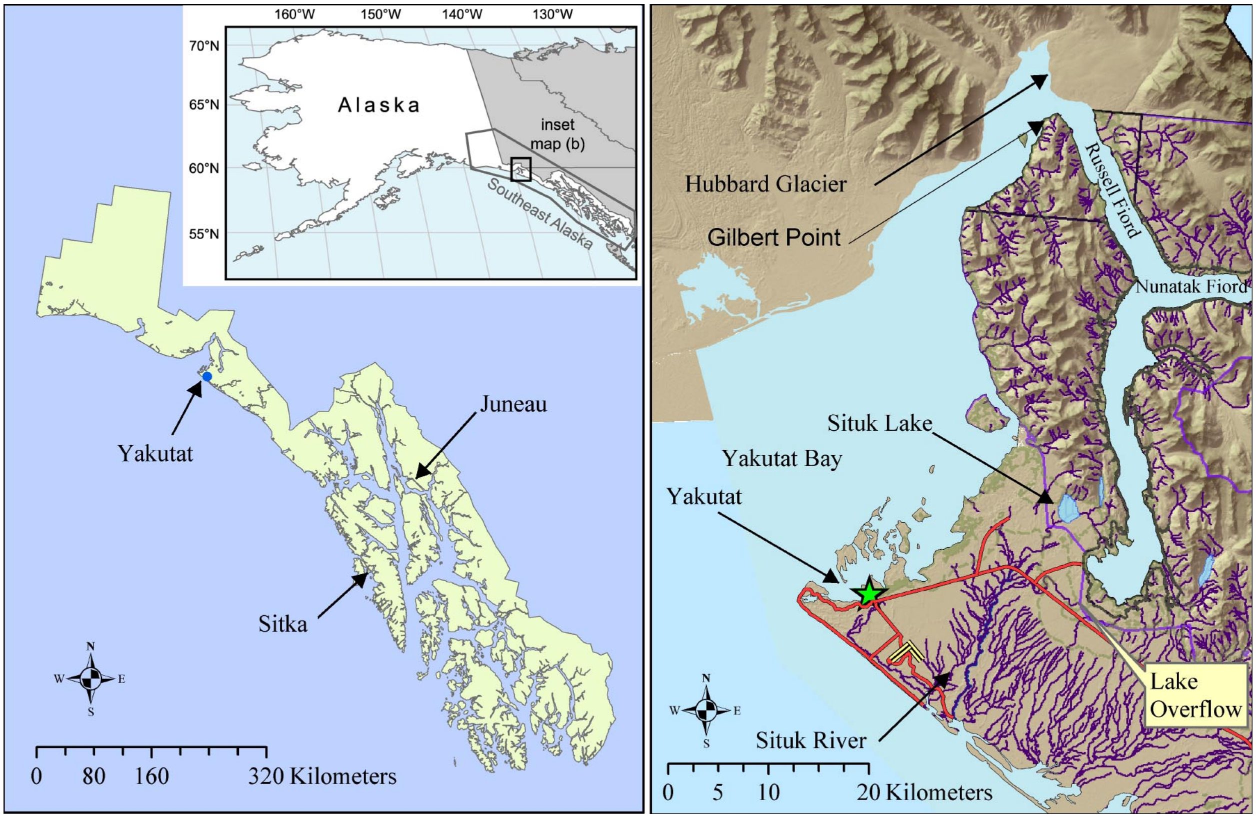
During the last 7,000 years, Russell Fiord in southeast Alaska has experienced cyclical ice damming by the Hubbard and Nunatak glaciers, forming a large lake that redirects outflow into the Situk River near Yakutat, Alaska. These cyclical events have continually altered the land and subsistence lifestyles of the local indigenous people (Tlingit). Oral traditions (deLaguna 1964) and geologic evidence (King 1995; Barclay et al. 2001) indicate that the last major ice dam failure occurred in the mid 1800s, transforming the Situk River into the present river system. The Hubbard Glacier most likely began re-advancing prior to 1791 (Barclay et al. 2001) forming temporary ice dams that created Russell Lake in 1986 and 2002. Future Russell Lake ice dam events could once again force major environmental and economic changes on the inhabitants of the area.

M Furniss, C Clifton, and K Ronnenberg, eds., 2007. *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004*, PNW-GTR-689, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Background

The Yakutat forelands and coastal mountains are one of the most geologically active areas on the North American continent. Nestled in the immense landscape near the mouth of Yakutat Bay is the small community of Yakutat (Figure 1). Yakutat's economy is almost entirely based on sport, commercial and subsistence fishing on the Situk River. Continued advance of Hubbard Glacier and potential permanent closure of Russell Lake, at sometime in the future, would have severe social and economic consequences for the residents of Yakutat and its outlying area. These concerns have spurred numerous studies during the 1986 and 2002 closures to better understand the geologic, hydrologic, biologic, and sociologic implications of such a major disturbance on the community and surrounding environment. During the 2002 Russell Fiord

Figure 1. Vicinity maps showing southeast Alaska and the Yakutat area.



closure, the USDA Forest Service, Tongass National Forest (lead agency) convened an interagency interdisciplinary team that included the Forest Service, US Geological Survey, Alaska Department of Transportation, National Park Service, University of Alaska and Army Corps of Engineers, to assess the affects on the Situk River and the Community of Yakutat. The work of the interagency team is ongoing and this paper reflects current and pending work completed to date. During the 1986 closure, a Forest Service team of technical specialists completed a floodplain analysis on potential inundation levels for the Situk River caused by the new Russell Lake and some possible diversion alternatives. The focus of the 2002 technical team was to update previous studies with more current information; perform stability analysis of the terminal moraine and ice dam; and determine feasibility of diversion alternatives. The results of these and future studies will address the following questions:

1. Will all flow from newly formed Russell Lake flow into the Situk River?
2. If flooding occurs, what are the risks to the community or to existing infrastructure?
3. Are the 1986 flow and floodplain assessments valid?
4. Is it feasible and by what method could Russell Lake be diverted into another drainage system?
5. Is the terminal moraine at the lake outlet stable?
6. Will the ice dam forming Russell Lake be persistent and stable at the next closure?

GEOLOGY

Glaciation

Most of the Yakutat Forelands landscape was formed from glacier outwash and moraine deposition processes within the last 1,000 years (Shephard 1995). Radiocarbon dates from debris buried in glacial outwash deposits indicate that there were at least two periods of recent advance, between the 13th and 19th centuries, by glaciers originating in the Barbazon Range east of Yakutat. The Nunatak Glacier (Figure 1), advanced to within 6 miles (9.7 km) of the head of Russell Fiord during the early 1800s, resulting in the most recent overflow of glacial Russell Lake into the Situk River system (King 1995). By the late 1890s, the Nunatak Glacier had retreated out of Russell Fiord (Gilbert 1904; Tarr 1909). The Hubbard terminus in 1895 was located about 2.4 km back from Gilbert Point (Figure 1) and the mouth of Russell Fiord (Trabant et al. 1991). Over the last century, Hubbard Glacier, currently the largest tidewater glacier in North America, has been strongly advancing while other glaciers in the area have continued to retreat (Trabant et al. 2003).

This advance-between 15 and 46 m per year-is likely to continue regardless of short-term climatic influences (Trabant et al. 2003).

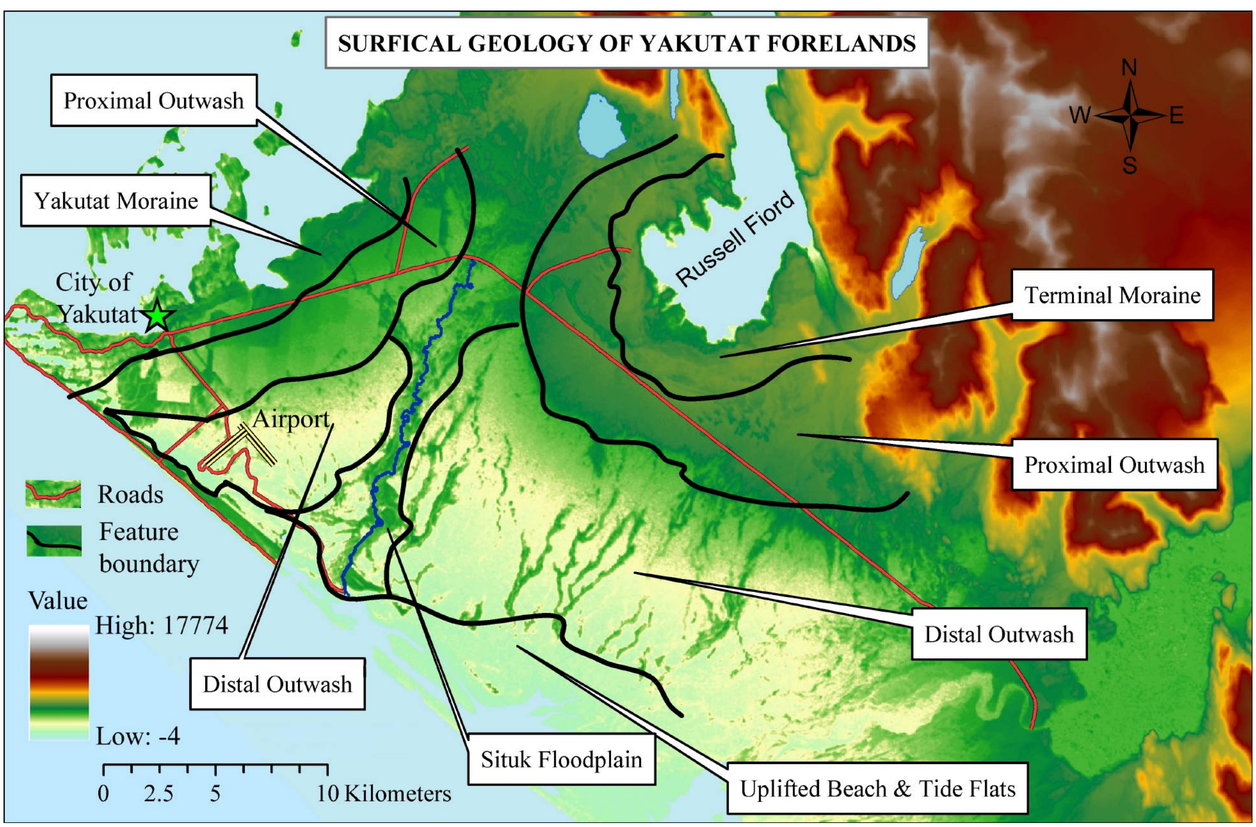
Over the last 20 years, seasonal advance of Hubbard Glacier has twice blocked the entrance to Russell Fiord, temporarily creating a large freshwater lake, Russell Lake. A shallow bedrock sill near the mouth of Russell Fiord allowed narrow fingers of ice and moraine deposits to close off the entrance to the fiord in 1986 and again in 2002. Russell Lake filled at an average rate of 0.2 m per day (Trabant et al. 2003) during the summer and early fall. In 1986, Russell Lake reached a maximum level of 26 m above sea level (maximum lake elevation in 2002 was 15 m) (Trabant et al. 2003). The incipient lake was strongly stratified by a freshwater-saltwater salinity gradient. The lower saltwater layer would have become anoxic (with no dissolved oxygen) in less than two years (Reeburg et al. 1976). However, the upper layer would be capable of supporting freshwater zooplankton and fish communities. A combination of hydrostatic pressure from the lake, erosion of the ice-moraine plug, and seasonal calving of the ice front resulted in catastrophic failure of both ice dams, producing the two largest outburst floods on record worldwide, 112,418 cms on 8 October 1986 and 52,386 cms on 14 August 2002 (Trabant et al. 2003).

Landscape Characteristics

The Russell-Situk watershed encompasses three major ecological subsections: Saint Elias-Fairweather Icefield, Puget Peninsula, Yakutat-Lituya Forelands (Nowacki et al. 2001). Headwaters in the Saint Elias Icefield reach elevations of over 2,743 meters. This ice mass covers 907 km^2 and feeds the Hubbard, Variegated, Nunatak, Hidden and Fourth glaciers. These mountain glaciers all terminate at or near sea level in Russell Fiord. The Puget Peninsula is a rugged mountain range that forms the western boundary between Russell Fiord and Yakutat Bay. Most of this area is barren rock with patches of alpine sedges, forbs and low shrubs. Lower mountain slopes have a dense cover of alder-willow shrub communities and isolated stands of black cottonwood (*Populus trichocarpa*) and Sitka spruce (*Picea sitchensis*). Russell Fiord covers an area of 199 km^2. The fiord has steep walls except for small river deltas and alluvial fans associated with the inlets of glacial rivers including Beasley Creek. These short glacial and steep mountain-slope stream segments provide very limited resident and anadromous fish habitat.

The Yakutat-Lituya Forelands is a low relief coastal plain formed by unconsolidated glacial outwash, moraine and recent fluvial deposits (Figure 2). This area has also been heavily influenced by isostatic rebound, tectonic uplift

Figure 2. Geologic map of glacial deposition, uplifted beach, and moraine features in the Yakutat area.



and subsidence, and long-shore ocean sediment transport and deposition. Vegetative cover is predominantly early successional spruce-hemlock forest and extensive bog wetland plant communities along Russell Lake (Shephard 1995).

The Russell terminal moraine (Figure 3) is a 1.6- to 3.2-km-wide deposit of unsorted glacial debris, ranging from silt- to boulder-sized glacial deposits. It extends from the south shore of Russell Fiord to the Forest Highway (FH) 10 crossing on Old Situk Creek. These better drained ablation tills are covered with a dense spruce-hemlock forest. Another, roughly 3.2-km-wide band of spruce-hemlock forest on gently sloping, proximal outwash deposits extends further to the south. Ephemeral streams exist throughout the proximal outwash zone. These outwash deposits consist mainly of highly permeable cobbles and coarse gravels (Shephard 1995).

The forelands contain numerous highly productive anadromous fish streams with the Situk River being the most prominent of these systems. Until about 1850, the Old Situk River-Situk River corridor (Figure 4) was the historic outlet to glacial dammed Russell Lake (de Laguna 1964). Narrow bands of cottonwood, alder, and conifer forests occur along current and abandoned floodplain terraces of the Situk River and its major tributary channels. Tree ring analysis of dominant conifers in the floodplain indicates that these trees were established shortly after the 1850 ice dam failure that drained historic Russell Lake (Clark and Paustian 1989).

The distal outwash (Figure 2) covers the bulk of the forelands adjacent to the Situk River corridor. This area is covered by fine-textured glacial-outwash sediment (gravel, sand, and silt). The water table is at the surface most of the year, forming the vast wetland fens and bogs in this area (Shephard 1995). Numerous small, palustrine streams initiate along the interface between the proximal and distal outwash zones.

Uplifted tidal flats and beach ridge landforms occur along the Gulf of Alaska coastline. This area, including the Situk-Arnkalin River estuary and Black Sand Spit (along the mouth of the Situk River), has recently been modified by earthquake, isostatic rebound and coastal erosion/deposition processes (Shephard 1995). The Yakutat area has had five major earthquakes since 1899, resulting in up to 15 m of uplift in portions of Yakutat Bay (Combellick and Motyka 1995). This tectonic activity altered groundwater tables and probably had long lasting effects on groundwater exchange with stream segments in affected areas. Isostatic rebound has also occurred over a much longer time span but may have resulted in more extensive changes to the lower forelands. Coastal areas near Yakutat have risen at a rate of 0.5 cm per year since 1940 (Savage and Plafker 1991). Portions of former perennial streams, such as Ophir Creek (adjacent to City of Yakutat), have become intermittent over the last few decades. Radiocarbon analysis of buried organic horizons exposed in stream banks indicates that uplifted beaches and tidal basins near the Situk River mouth were formed within the last 150 years (Shephard 1995). Long-shore transport and deposition of sediment derived from large glacial rivers is another significant agent of coastal change. Expansion of Black Sand Spit has pushed the mouth of the Situk River 2.4 km to the northwest over the last 50 years (Shephard 1995).

Figure 3. Oblique aerial view of the Russell terminal moraine. Note the parallel sequence of moraine ridges bisected by relic glacial drainage paths. The high water level from the 1986 ice dam event is marked by the band of dead trees along shoreline of Russell Fiord.

Figure 4. Oblique aerial view of the Old Situk River–Situk River corridor.

HYDROLOGY

Unique landscape and climatic factors strongly influence major hydrologic events in the Russell-Situk watershed. The Yakutat area has a wet, cool, maritime climate

Figure 5. Russell Lake (circa 1986) looking north toward Hubbard Glacier.

typical of southeast Gulf of Alaska coast. Average annual temperature at the Yakutat NOAA weather station is 4°C . Typical mean air temperature is in the 0-5°C range during winter and 10-16°C during the summer. Normal annual snowfall is 510 cm at the coast, with a maximum of 10.2 m recorded in the winter of 1975-76. Average annual precipitation in Yakutat is 380 cm. No climatic data are available for the Russell Fiord and Saint Elias Icefields; however, annual precipitation is estimated to be between 410 cm and 559 cm. Except for periods during the summer months, precipitation in the icefield portion of the Russell Lake watershed falls as snow.

Almost 50% the Russell Lake watershed area (Figure 5) is covered by permanent snow and ice fields. Runoff into glacial Russell Lake is greatest during maximum snow and glacier melt in the summer months, and decreases considerably during the remainder of the year.

Russell Lake

The USGS lake gage at Marble Point, operated during the 1986 and 2002 ice-dam closure events, measured an average lake inflow rates from 425 cubic meters per second (cms) to 538 cms (Trabant et al. 2003; Neal 2004). A large portion of the Russell Lake watershed area is lake surface (11%) and rock or shallow alpine soils (30%), characteristics that result in rapid runoff during high intensity summer rainfall. Large spikes in the lake inflow hydrograph, as high as 2,605 cms, occurred in response to short-duration, high-intensity, summer rainfall events in August of 1986 and 2002. Rainfall intensities for these two events approached the maximum 24-hr and 12-hr August rainfall records (14 cm and 8 cm respectively) for the Yakutat weather station. It is interesting to note that even though these rainfall events were of similar intensity and duration, the peak lake inflow rate observed in 2002 was almost double the peak inflow rate in 1986. These data suggest that factors such as moraine/ice dam leakage, variability in basin rainfall distribution, or englacial runoff from Hubbard Glacier may significantly influence short-term inflow rates to Russell Lake.

Russell Lake inflow rates for selected return intervals (Table 1) were calculated using two approaches: 1) regional equations, based on basin characteristics (Curran et al. 2003); and 2) a regression model, based on 2002 lake gage data correlated to stream gage data from Situk River and Ophir Creek (Neal 2004). Russell Lake peak inflow estimates were also derived using regional equations (Curran et al. 2003). Regional equation variables include: total basin area (1,927 km^2), annual precipitation of 559 cm, and minimum January temperature of -9°C. The regression equation contains a percent of lake in the basin, set to a value of one to remove lake storage effects. Results of the both methods are listed in Table 1. It is important to note that the Russell watershed characteristics are significantly different from watershed characteristics of gaged basins used in the development of the regional regression equations, increasing the uncertainty and reducing the reliability of these inflow rates.

Neal's regression approach used lake-gage data from 16 July to 13 August 2002 when leakage from the moraine/ice dam was observed to be minimal. Stream gage data from eleven Ophir Creek and Situk River peak flow events (between 15 May and 15 October for water years 1991-2002) were used to develop a synthetic Russell Lake inflow hydrograph (Table 1) (Neal 2004). Neal's synthetic peak discharge estimates (Table 1) are much higher than peak flow estimates derived from the USGS regional equations. These estimates represent a best approximation for the range of peak Russell Lake inflows given limitations in the available data used to derive both sets of predictions.

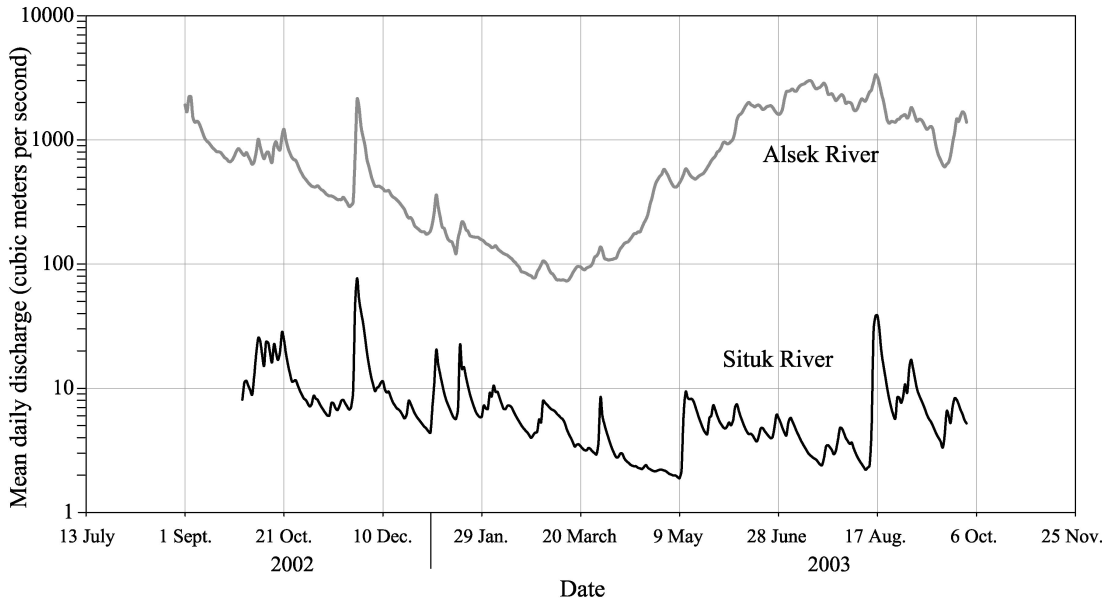
Situk River

The headwaters of the Situk River (Figure 1) emanate from the Puget Peninsula, Mountain Lake, and Situk Lakes. Major tributaries are the Old Situk River, draining

Table 1. Russell Lake inflow predictions from regression model and regional equations (after Neal 2004).

Recurrence Interval (yrs)	Synthetic Model Discharge (cms)	Regional Equations Discharge (cms)
2	4,171	2,163
50	6,397	4,078
100	6,759	4446

Figure 6. Mean daily flow hydrograph for the Alsek River and Situk River in cubic meters per second.



the Russell Moraine (also the historic overflow channel from Russell Lake) and West Fork Situk River, that drains the Redfield Lakes and the eastern portion of the Yakutat Moraine. Numerous small palustrine streams enter the Situk along the distal outwash plain. Ophir-Tawah Creek and Lost River are the most prominent tributaries in the lower Situk River watershed.

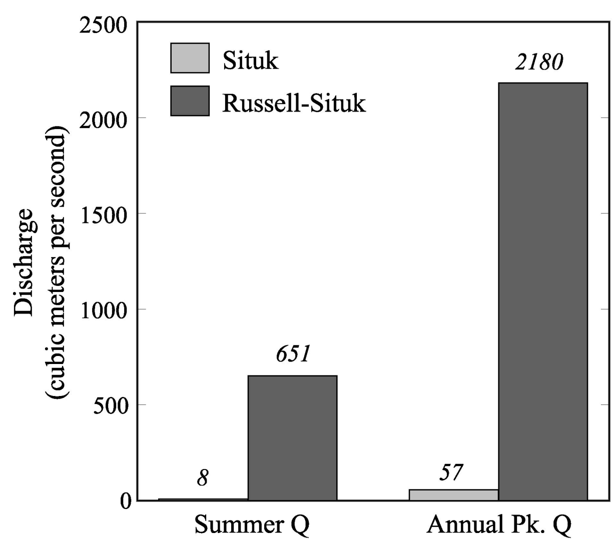
Peak flows in the middle Situk drainage basin (93 km^2) are generated by prolonged periods of high rainfall in the fall and early winter (Figure 6). Base flows are relatively stable during the remainder of the year. Groundwater derived from the moraines and proximal outwash landforms are a major component of river base flow. Storm hydrograph peaks, however, have a relatively short duration of 1 to 3 days.

The basin area for the entire Situk River drainage would increase from 215 km^2 currently, to over 2,072 km^2 with the addition of the Russell Lake basin area (Clark and Paustian 1989). Future Russell Lake overflows into the Situk River drainage will result in the dramatic changes of a one hundred-fold increase in average summer river discharge to the Situk River flow regime (Figure 7). Figure 6 contrasts seasonal hydrographs for the middle Situk stream gage and a nearby stream gage on a large glacial river, the Alsek River. The Alsek River is a much larger watershed and has lower annual precipitation, but has a geologic setting similar to Russell Lake. Glacially dominated runoff from Russell Lake will also shift peak flow timing in the Situk from the fall and winter months to the summer season (Figure 6).

Mean summer discharge in the Situk is currently between 5.7 and 8.5 cms. In contrast, Russell Lake gage measurements from 1986 and 2002 indicate that summer flows in the Situk River associated with the greatly expanded Russell-Situk drainage basin will be between 425 and 850 cms (Figure 7). Maximum daily peak discharge measured for the Situk River (from 1988 and 2004) is 92 cms. Annual peak discharge (2.33-year flood frequency) for Russell-Situk watershed is predicted to be 2,186 cms (Miles 2004).

Groundwater tables in the distal outwash zone of the lower Situk River watershed are within 1 m of the surface. A series of dry gravel borrow pits along FH 10 indicates that water tables are relatively deep in the proximal outwash zones. Proximal outwash and some moraine deposits are

Figure 7. Comparison of the current Situk River streamflow with the predicted Russell Lake-Situk River flow.



well drained, however, kettle ponds and bogs are common in depressions that have been sealed by silt deposits and fine organic material (Shephard 1995).

Due to the heterogeneity of moraine deposit sediments, permeability changes both laterally and vertically. The terminal moraine at the head of Russell Fiord has seen several glacial advances (shown in Figure 3 as parallel ridges) and retreats with associated lake formation. We speculate that these glacial advances and retreats have contributed fine materials (silt and rock flour) to the subsurface moraine material, greatly reducing hydraulic conductivity of the moraine or making it impermeable, similar to a clay plug in an earthen dam. Although field observation along the Russell Lake side (northwest corner) of the moraine face validates this assumption, additional geophysical data is required to verify consistency across the moraine.

Monthly groundwater levels are stable for much of the year, with the exception of depressed levels in June and July, which correspond to low rainfall and minimal snow pack inputs (Clark and Paustian 1989). Segments of small palustrine and floodplain tributaries (including Ophir Creek) become intermittent during short summer droughts.

The Old Situk River channel was the historic outlet of glacial Russell Lake for an unknown period of time during the early to mid 1800s. Oral history accounts of the Tlingit Indians (de Laguna 1964) and dendrochronology data from the Situk flood plain and shoreline of Russell Lake (Clark and Paustian 1989; King 1995) indicate that the Nunatak Glacier ice dam failed around 1850, severing the Situk watershed connection with the Russell Lake watershed. The 1800s ice dam location (approximately 10 km from the head of Russell Fiord) resulted in a much smaller lake (and smaller watershed area), than was associated with the 1986 and 2002 dams at Gilbert Point near the mouth of Russell Fiord (King 1995). We speculate that runoff volumes from the Old Situk Notch, which formed the relic Situk floodplain channels (Figure 4) prior to the Nunatak ice dam failure, are potentially an order of magnitude smaller than the runoff volume that would result from a semi-permanent Hubbard Glacier ice dam located at Gilbert Point.

Terrain Modeling

Data Acquisition

One of the keys to modeling Old Situk-Situk River flood plain characteristics is accurate elevation data. Terrain on the forelands has very low relief and is composed primarily of bogs and fen complexes with grass and sedge of various heights (Shephard 1995). Most streams have a riparian corridor consisting of dense Sitka spruce, willow, and devils club (*Oplopanax horridus*). The terminal moraine and proximal outwash is heavily forested with Sitka spruce and *Vaccinium* understory. Vegetation influence is always an issue in determining true ground elevations especially in areas of dense vegetation. The original 1986 floodplain assessment relied on elevation data generated by USGS using analytical photogrammetric methods from air photos flown during leaf on conditions. The ability to get sufficiently dense and accurate data reflecting actual ground elevations and not the top of vegetation with this type of technology is difficult and a potential source of modeling error, which becomes more significant in areas of very low relief.

A test flight using LIDAR (Light Detection and Ranging) technology was made in 2002 to determine if accurate elevation data could be obtained along the Situk River during leaf-on conditions. LIDAR data provides a quick way of obtaining and mapping elevation data in terrain that is logistically difficult to access. LIDAR uses a tagged laser pulse that records the return time of the laser pulse and keeps track of the airplane position and orientation (roll, pitch and yaw), yielding elevation data that is accurate to 15 cm vertically and 1 m horizontally. To validate the LIDAR elevation data, survey grade GPS controls were established to test profiles surveyed along the river corridor on the forelands and terminal moraine. All survey data were transformed into the same coordinate system (NAD 27 NGVD 88). The ground surveyed profiles were very similar to those produced by the LIDAR data. The elevation accuracy between the two data sets (Table 2) led to the acquisitions of LIDAR data for the entire Situk River floodplain and remaining areas around the terminal moraine. The data was processed with a vegetation removal algorithm similar to the method described by Haugerud and Harding (2001) to remove ~99% of the vegetation points. Although this is an automated procedure, some additional manual processing may be necessary to remove vegetation anomalies along the dense riparian corridors. The ASCII ground point files of the LIDAR data were so dense that further thinning by gridding the points was necessary for the floodplain inundation models to be continuous from the ocean to

Table 2. Comparison of LIDAR elevations to ground surveyed profiles.

Location	Mean Difference (m)	Std. Dev. (m)	RMSE
Old Situk River Notch	-0.31	0.41	0.16
Section 10 on Forelands	-0.30	0.31	0.03

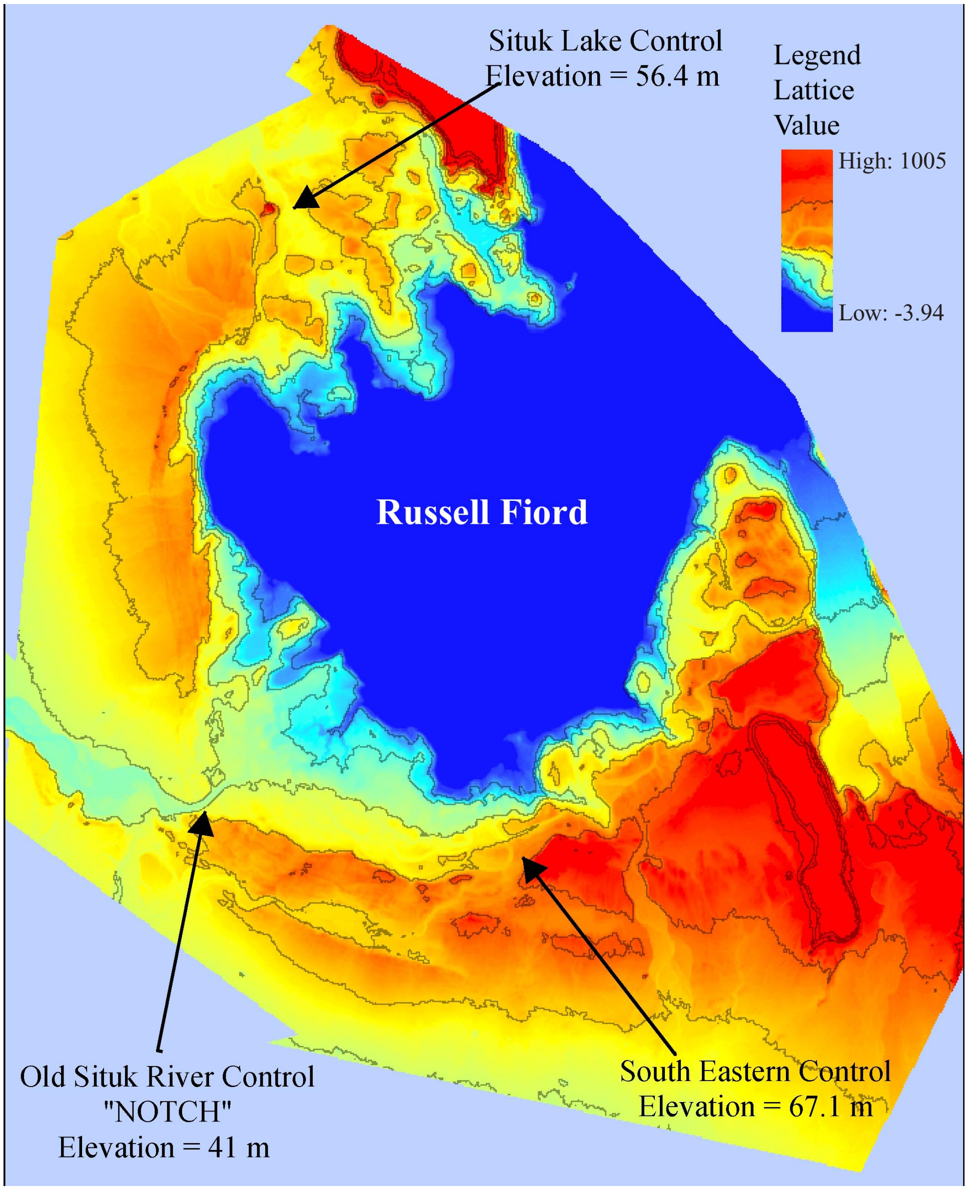


Figure 8. LIDAR derived DEM showing outflow controls for historic Russell Lake.

Russell lake boundary conditions. The LIDAR data was dense enough to show all of the geomorphic expression of the moraine and floodplain landscapes (Figure 8).

LIDAR data acquisition was difficult due to the remoteness of the project area, poor weather (low cloud ceiling and precipitation), and LIDAR operator flight requirements (minimum of 1000 m above ground level). These difficulties, in addition to needing a dedicated helicopter for ground surveys and the urgent need for data, drove costs higher than normal for both LIDAR and ground surveys (Table 3). Further LIDAR data collection efforts are planned to obtain elevation data across the forelands to determine the feasibility for creating diversion channels.

Table 3. Survey accomplishments and costs for LIDAR and ground surveys.

Year	Ground survey (km)	Ground survey costs (2004$)	LIDAR Area (hectares)	LIDAR costs (2004$)
2002	19	$275,000	12484	$89,000
2003	-	-	20914	$151,000

Lake Flow Controls

One of the purposes of the LIDAR survey was to obtain detailed topography along the terminal moraine to map all potential overflow points. All previous assessments have mentioned only the Old Situk River Notch as the main lake outlet control. The Old Situk Notch was validated as the outlet control, however, the LIDAR survey also revealed additional control elevations of several historic Holocene outlets that contain underfit streams (streams too small to have carved their valleys). Three main Holocene lake level controls are identified (Figure 8). The identification of these other spillways is important in understanding their relations to maximum projected lake level since the current lake size (and inflow volume) is approximately double that of the last closure.

To identify historic Holocene lake controls, the LIDAR data were transformed into a lattice grid in ESRI ArcInfo[1] . The grid was then incrementally assessed using the analysis map query tool in ESRI ArcView to develop coverages that show all elevations greater than a given elevation. This process was repeated every 1.5 m until the major overflow controls were identified. The control areas (Figure 8) were then evaluated using terrain modeling software (Spectra Precision TERRAMODEL V 9.7 2000). The model's gridding process averages elevation from the point coverages to form an equally spaced set of gridded elevations. This process can slightly alter the actual control elevation. The LIDAR points were recontoured in TERRAMODEL to compare the results. As the exact location of the LIDAR points on the ground cannot be controlled due to vegetation point removal, track and swath spacing, and collection of the LIDAR sensor, the overflow elevations reported are based on the ArcView analysis with potential lower limit elevations developed in TERRAMODEL. Both methods produced similar results. Overflow and lowest possible elevations were determined for each lake control. For the Old Situk River control, values were 41 m and 40.2 m, respectively; for Situk Lake control, 56.4 m and 55.2 m; and for the southeastern control, 67.1 m and 66.5 m.

The terrain modeling results show that all outflow from Russell Lake will drain through the Old Situk River control notch when the lake levels rise above 41 m. Our floodplain analysis evaluated discharges of 566 cms for normal flow, 2186 cms for a 2.33-year flood, 4446 cms for a 100-year flood, and 6796 cms for the maximum flood, and produced estimated lake levels of 45.3 m , 49.2 m, 52.6 m, 54.6 m respectively. These estimates are well below the 56.4 m Situk Lake elevation control; therefore this outflow location will not affect Situk Lake or the 10 km of prime salmon & steelhead spawning and rearing habitat in the upper Situk River drainage (because these areas are above the mainstem junction with the Old Situk River channel).

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

HYDRAULIC FLOOD MODELING

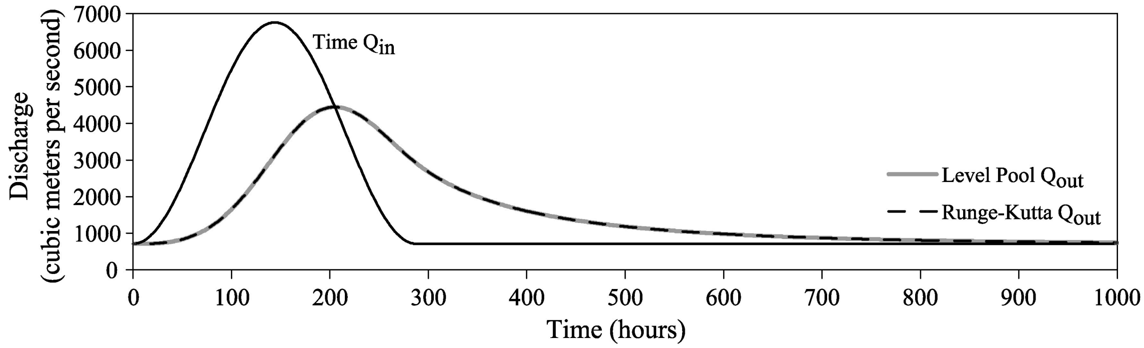
Hydraulic flood modeling was done in order to identify floodplain inundation limits with improved elevation data and determine lake levels and potential overflow points along the terminal moraine. A flood assessment of this magnitude is difficult to predict because of continual changes in channel characteristics (width, depth, shape), and the effects of roughness (form roughness, log jams) as flow progresses from initial overtopping of the moraine to some point in the future when a more stable system will develop. The geomorphic expression of the old Situk River on the proximal and distal outwash provides anecdotal evidence of historic flood limits. However, historic Russell Lake was believed to be 50% smaller than the current lake and watershed area. This factor will increase projected lake overflow volume to the Situk River corridor.

Russell Lake Outflow and Reservoir Routing

Once the lake level reaches 41 m above mean sea level, water will overtop the Old Situk River spillway. The volume of lake outflow is controlled by the height of the water above the spill crest. For the analysis, a stage-discharge relationship was developed assuming the spillway is a rigid boundary. The elevation and spillway geometry of the Old Situk River control should be sufficient to handle outflow from Russell Lake, preventing the lake from rising to an elevation that would cause outflow to occur at the Situk Lake control (Figure 8). The Old Situk River control has the capacity to convey a discharge of 7100 cms, which is 1.6 times greater than the estimated 100-year flood discharge.

Lake systems provide a storage function for inflow hence Lake outflow = inflow - storage. The elevation rise in a lake is a function of hypsometry (storage volume versus elevation) and inflow. The amount of storage for various floods needed to be calculated to determine peak outflow rates. An inflow hydrograph is the first step in the analysis; the shape and duration of this hydrograph greatly affects the model results. No inflow hydrograph existed, so a synthetic hydrograph was developed. The storm history of the Yakutat area and simulated hydrographs developed by the USGS inflow study (Neal 2004) indicated that a time to peak flow of four to six days for a "standard" was a reasonable assumption (Miles 2004). A base flow of 708 cms with six-day duration to peak inflow was used in a simple sine function to develop the shape of the inflow hydrograph. Two methods of reservoir routing (Runge-Kutta and Level Pool) were used with the data from the inflow hydrograph, lake hypsometry and outflow stage discharge relationship resulting in similar outflow

Figure 9. Russell Lake Inflow and Outflow Hydrograph for the 100-year flood.. Both the Level Pool and Runge - Kutta methods which predict similar results and are not visible separately on this graph. (Miles 2004) Qin is the inflow rate and Qout is outflow rate.



hydrographs (Figure 9) (Miles 2004). Flood routing results are shown in Table 4 (Miles 2004).

Flood Modeling

Computer open-channel flow models assume a "rigid" boundary. This rigid boundary assumes that the channel bed and margins do not mobilize or erode, changing shape with discharge. In the case of the Situk River, the distal outwash is unconsolidated fine-grained gravel and sand. Depending on flow stage, a portion or entire channel sections will be mobilized and margins will erode until the system reaches some form of "dynamic equilibrium". The modeling done to date assumes a rigid boundary, which will produce higher water levels compared to the existing topography than the likely future channel due, to incision and channel formation. Our current intent is to identify potential impacts on public safety and infrastructure, and note areas of where mobile bed conditions may exist. Two models were used to evaluate flood characteristics on the Situk: the dimensional steady state flow model HEC-RAS V3.1 from the U.S. Army Corps of Engineers (US ACoE 2003), which assumes average flow velocities perpendicular to the cross sections evaluated; and the two-dimensional flow model SMS/Flo2DH (BYU and FHA 2004), from Brigham Young University and the Federal Highway Administration, a finite element analysis that solves for flow in the horizontal plane assuming vertically averaged flow velocities for each element.

Table 4. Flood routing analysis (after Miles 2004). Routed outflow discharge results indicate a significant storage capacity in Russell Lake that substantially attenuates inflow peak discharge.

Recurrence Interval	Inflow		Outflow	
(years)	cms	cfs	cms	cfs
2	4,171	147,300	2,107	74,400
2.33 (mean annual)	4,332	153,000	2,186	77,200
50	6,397	225,900	4,174	147,400
100	6,759	238,700	4446	157,000

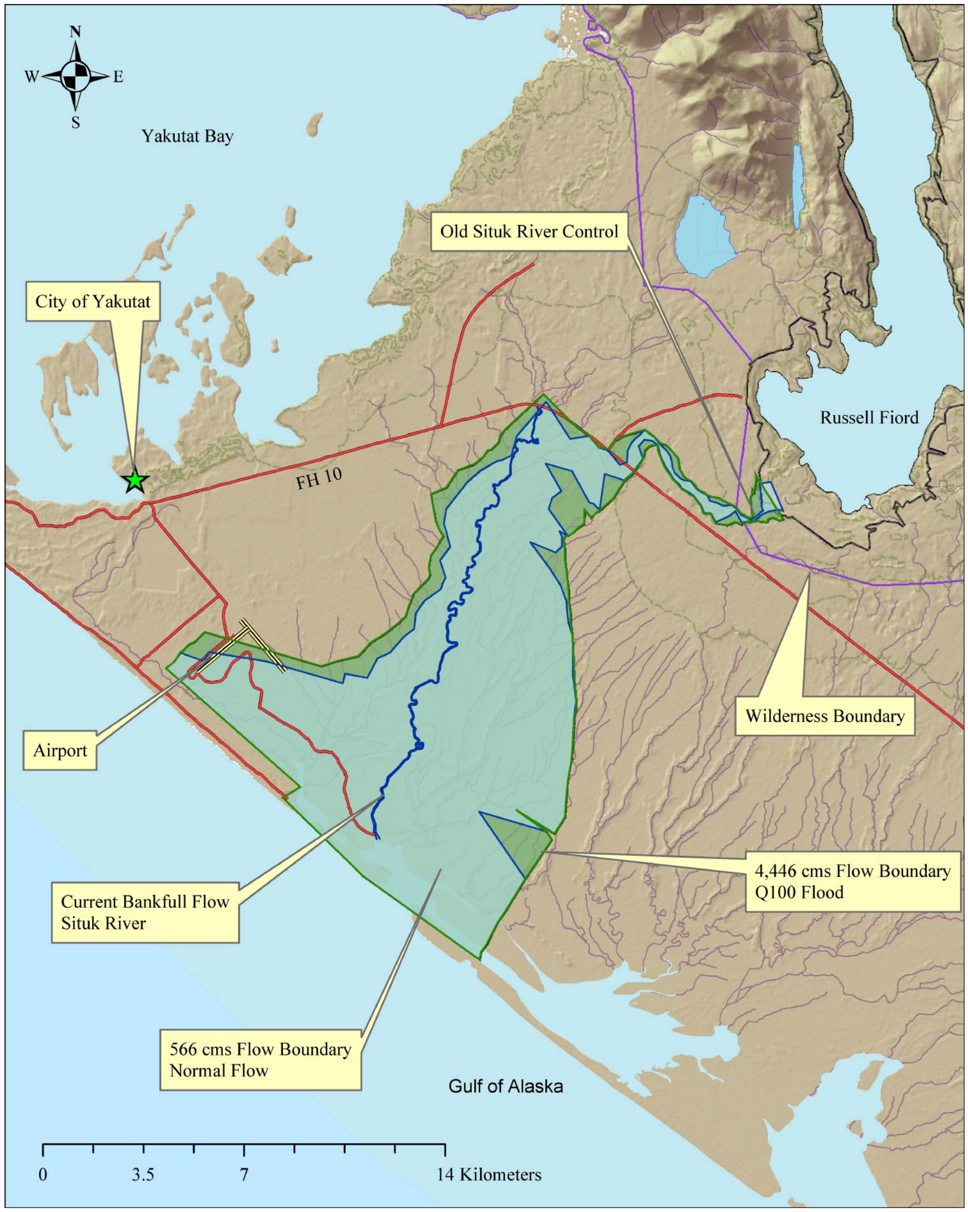
Modeling Assumptions

The channel cross sections used in modelling were based on the existing topography and assumed to be rigid. Even though both lateral and vertical scour is expected, the amount of channel scour cannot be reliably estimated until geotechnical drilling verifies the subsurface material characteristics of the bounding channel walls and bed. Roughness of the channel greatly effects water surface elevation. It is anticipated that log jams will form randomly through the system, causing large fluctuations in roughness. Current predictive capabilities have high uncertainty, so estimates of roughness are based on operator experience, and assume that a portion of the woody debris has been removed by high water (Miles 2004). Both models require inputs of boundary conditions. The upstream boundary condition is the outflow from Russell Lake and the downstream boundary condition used is the high tide line at ~3 m above mean sea level, where the Situk River meets the Gulf of Alaska. Both programs are capable of unsteady flow analysis, when discharge varies over time. To reduce the complexity of the model, a simplified steady state (constant) flow for peak flows was assumed. Peak flow is expected to occur for an adequate length of time, making steady flow a reasonable assumption (Miles 2004). No attenuation of peak flows was used in the model, providing a conservative analysis due to public safety concerns for Yakutat.

Model Results

The HEC-RAS model was based on seventy-eight cross sections over a 35 km (21.6 mi) length of channel. For all the flows modeled (Q_2 to Q_{100}), the Situk River control acts as a spillway using its current channel configuration,

Figure 10. Floodplain inundation map based on HEC-RAS modeling and a rigid boundary assumption.



with the actual hydraulic control being approximately 732 m (2400 ft) downstream (Miles 2004). Along the Situk River control segment, the model produced supercritical flow (Froude # = 1.1 to 1.5) with extremely high velocities of Q_2 = 7.6 m/s and Q_{100} = 10.1 m/s. The two short segments of the Situk River that had supercritical flow are narrow and deeply incised sections within the moraine. These zones of supercritical flow are expected to change channel configurations from scour due to high velocities and water surface slopes. All other sections of the Situk River are, as expected, in subcritical flow regime.

Floodwaters exit the proximal outwash onto the forelands approximately 8 km (5 mi) downstream of the Old Situk River control immediately below FH10 (Figures 1 and 4). At this point topography changes, rapidly becoming less confined with well developed floodplains further downstream. In this area, floodwaters inundate the floodplain to varying widths, depending on magnitude of the flood. For the 2-year (Q_2) and 100-year (Q_{100}) flood return intervals, widths ranged from 0.6 and 1.3 km at FH10, to 7.5 and 8.0 km approximately 9.7 km (6 mi) upstream of the Situk outlet, and 14.4 km (9 mi) for both flows at the mouth of the Situk River (Miles 2004). (Figure 10)

To construct the SMS/Flo2DH model, the dense LIDAR data required "weeding" to a 15-m (50-ft) spacing and required the river corridor to be divided into three sections with a total of 27,000 elements and 56,000 nodes (Miles 2004). Only the Q_{100} flood (4446 cms) was analyzed with the 2-D model, and surface water elevations predicted were similar to those of the HEC-RAS Model (Table 5). The model could not predict a stable solution for a short

Table 5. Comparison of computed water surface elevations at selected sites (Miles 2004).

Location	River Station	Ground Elevation (m)	HEC_RAS $Q_{2.33}$ (m)	HEC_RAS Q_{100} (m)	Flo2DH Q_{100} (m)
Outlet	448.4	- 1.8	3.0	3.0	3.0
Threshold Runway 2	3210.1	3.4	Dry (3.1)	Dry (3.3)	4.6
Threshold 29	5917.2	5.6	5.6	6.1	Dry (5.5)
Mid Yakutat Forelands	6436.3	3.9	5.9	6.4	6.0
Mid Yakutat Forelands	10745.3	7.3	9.2	9.8	10.4
Situk-Old Situk confluence	21785.5	17.3	20.3	21.0	20.3
Forest Highway 10	26068.8	26.3	29.6	30.7	30.3
Area below lake control	32776.2	36.5	40.8	43.5	NC
Russell Fiord	34830.0	NA	49.2	52.6	52.6

915-m section of river immediately above FH10, because of rapidly varied flow conditions and multiple flow paths (Miles 2004).

GEOPHYSICAL SURVEYING

Because outflow from Russell Lake will drain through the Old Situk River control notch, it was important to better characterize the subsurface conditions of this feature. In summer 2003, preliminary seismic and ground penetrating radar (GPR) surveys were conducted in the Old Situk River control notch. These surveys were intended to determine if the methods used could differentiate the thickness of the armored channel, fine-grained unconsolidated materials, and potential bedrock surface. The "Notch" is located within the Russell Fiord wilderness boundary, precluding the use of helicopters and all-terrain vehicles. Seismic and GPR surveys were used because the equipment is portable by backpack, and the methods required minimal ground disturbance and vegetation clearing. No calibration data were obtained from drilling because of limited access through the wilderness and funding constraints. This is a concern, because the geophysical assessment is based on interpretation of remotely sensed images, mapped stratigraphy near the southern portion of Russell Fiord (King 1995; Tarr 1909), observed exposures of sediments and surficial armor in the Old Situk channel, and limited drill data on the forelands near Yakutat (Yehle 1979).

The Russell Fiord terminal moraine is geologically complex, since it was probably formed by both tidewater and terrestrial glaciers. This complexity means a single survey method often may not be suitable to characterize the moraine and outwash areas, hence the decision to use both seismic and GPR techniques. Each technique has limitations and strengths, and using both geophysical techniques will improve the subsurface interpretation, as data from each can be compared and correlated.

Ground Penetrating Radar

GPR measures the contrast in dielectric properties of the subsurface materials through which electromagnetic waves of a given frequency (radio waves at 25 MHz to 1 GHz) travel (Philip 2004). As the electromagnetic waves propagate through the subsurface materials, some of the waves are reflected and absorbed, while the remaining waves are transmitted at boundaries between layers of materials that differ in physical properties and dielectric constants. Image resolution and penetration depth vary depending on the antennae frequency with greater penetration depth occurring at lower frequency antennas (25 MHz - 50 MHz) and increased image resolution occurring at higher frequency locations (500 MHz - 1 GHz) (van Overmeeren 1994). A MALA Geoscience RAMAC GPR system with Groundvision V1.3.6 software was used to record and process the data with 50 MHz unshielded antennas for maximum penetration because the unknown depth to bedrock in the notch area. Radio waves pass readily through geologic materials with low dielectric constants such as sands and gravels, while materials with high dielectric constants such as clay-rich layers can attenuate or block the signal entirely (Philip 2004). When large contrasts in dielectric constants exist, strong reflections are observed. This is the primary means of identifying subsurface features, but GPR becomes limited with depth because of reduced signal strength and resolution (Figure 11).

Deriving the GPR wave velocity allows conversion of travel time to depth and development of subsurface stratigraphic models (Philip 2004). Wave velocity in a subsurface materials can be described by the following equation:

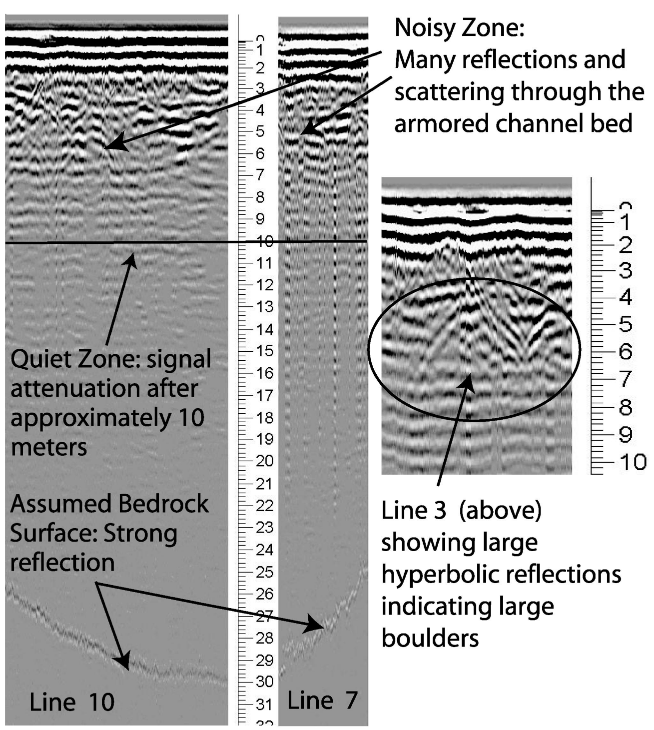
$$V = \frac{C}{\sqrt{e_r}}$$

where: V = velocity (m/s); C = speed of light in free space (m/s); e_r = relative dielectric constant.

Since e_r is unknown, a common midpoint survey was used to determine velocities. The transmitter and receivers are placed around a common midpoint, a measurement is taken and the transmitter and receiver are moved apart incremental distances until several data points are collected. A plot of T^2 vs. X^2 (2-way return time versus distance) is constructed and the slope of a best-fit line yields the squared wave velocity (Beres and Heini 1991). Four common midpoint surveys were performed with an average derived velocity of 64 m/μs with a standard deviation of 5.5 m/μs. This average velocity was used to calibrate the radar images in Groundvision V1.3.6, to determine the depth to reflection events along the GPR survey lines.

Ideally a continuous GPR survey line length should be five to ten times the depth to the surface of interest (bedrock). This was not possible because of the dense Sitka spruce stand in the Old Situk River control survey area. Twelve GPR transects varying from 10 to 40 m where surveyed. The Old Situk channel bottom is very rough, with a predominately boulder armored surface (Figure 12). This type of material made it difficult to find transects where full antenna contact could be made with the ground.

Figure 11. Ground penetrating radar images showing three distinct zones including an upper noisy zone of boulder armor, a quiet middle zone and a lower bedrock surface.



Seismic Refraction

Seismic refraction has been used successfully in various environments and conditions to measure the depths of materials and locations of the subsurface interfaces for engineering, mining and research applications. Seismic wave refraction is the travel path of acoustic waves through an upper medium, along an interface at a critical angle, and back to the surface. These interfaces are interpreted as different materials or changes in density. The propagation of acoustic waves through different mediums follows Snell's law of light refraction, which describes the geometry of wave travel paths, allowing standard techniques to recover layer velocities and depths (Philip 2004).

Seismic data are processed by taking the first arrival of the signal for each geophone, and plotting the return time from acoustic source (sledge hammer) to geophone versus the distance the wave traveled from the acoustic source. The inverse slope of the return time versus distance plot allows the determination of seismic wave velocities through the layers of material.

An acoustic source was applied to both ends of the transects to obtain forward and reverse shot data. This is a standard procedure to test for asymmetric travel times and lateral velocity changes as well as any dip angle of different material layers. A Geometrics SmartSeisSE 12-channel seismograph was used to collect seismic refraction data with Geophone spacing that ranged from 1.5 to 5 m, depending on terrain and length available for each survey transect. Data was processed with SIPWIN software from Rimrock Geophysics. This software allows the operator to input multiple spreads, acoustic source locations, and reverse lines.

Geophysical Survey Results

The GPR images show numerous reflections in the first several meters of depth, followed by a marked absence of reflections below 10 m. Large hyperbolic reflections (Figure 11) indicate large boulders in the channel subsurface that are probably similar in nature to those observed on the channel surface, and located 5 to 7 m below the channel surface. Below 10 m, signal strength is markedly weaker (Philip 2004). Though there is no clear location of the boundary, this signal attenuation is most likely caused by a clay-rich conductive layer. This clay-rich layer corresponds with the upper stratigraphic sections mapped by King (1995) in the lower Russell Fiord area that contained thinly laminated clay, silt, and sand layers at approximately the same depth. A strong reflection is shown in all GPR images at approximately 30 m below the Old Situk River control. The shape and location of this reflector is consistent

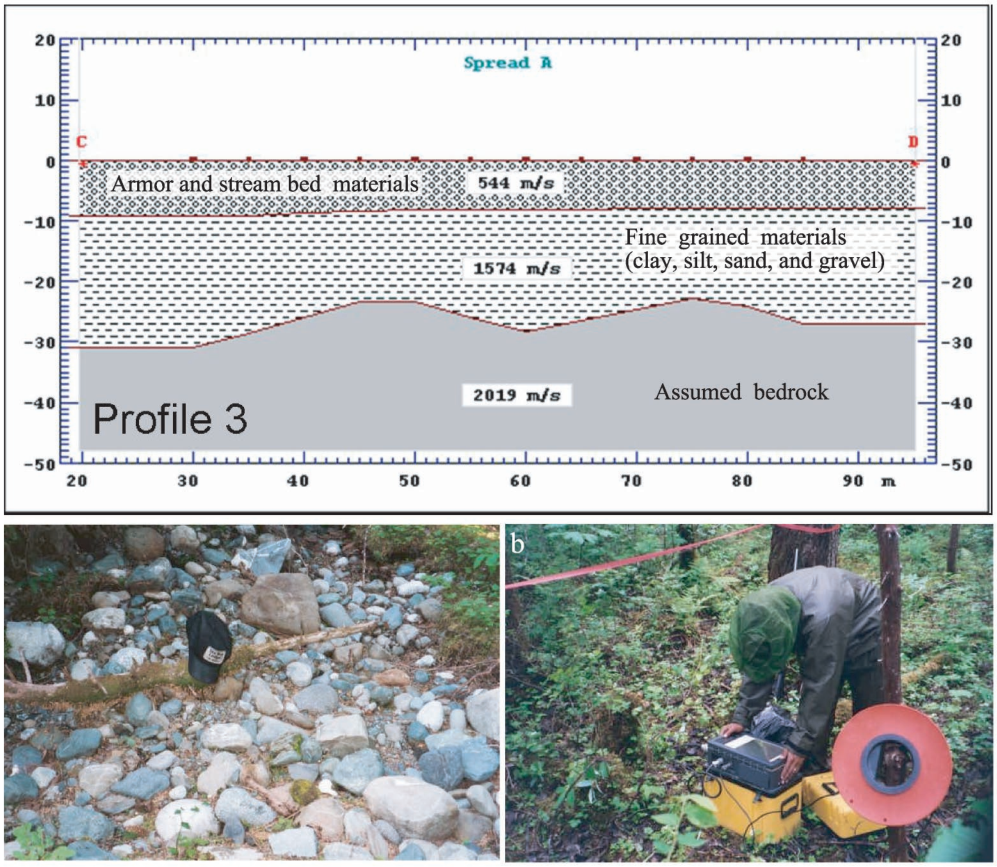


Figure 12. Seismic refraction 3-layer results with recording equipment and existing surface conditions
(a) left – Boulder / cobble armored channel bottom in the Old Situk River Notch. Heavy armor and rough surface of historic channel bottom made GPR surveying difficult and limited in scope.
(b) right – Geometrics SmartSeisSE 12-channel seismograph.

through several of the images and was interpreted as bedrock (Philip 2004). The beginning of Line 7 is nearly coincident with the end of Line 10 in the field (Figure 11) and the radar images show the bedrock reflector at the same depth at this location. The presence of this bedrock reflector is consistent across other GPR lines that cross one another. However, drilling on the moraine demonstrated that the suspected bedrock turns out to be a massive fresh water saturated silt layer of glaciolacustraine origin. The silts are slightly plastic and the high water contentand silt layer gave the strong reflection. It is important to verify and calibrate your remotely sensed data with borehole data to make it more reliable for analytical use.

The seismic data showed results similar to the GPR. The 2-layer partitioning of the data shows a change in density at ~15 m of depth. Only two seismic transects were long enough to give reasonable travel times to derive a three-layer solution. Images generated from three-layer seismic refraction data show refractors occurring at about the same depths, 10 and 30 m (Figure 12). The calculated velocities for the upper layer are <1000 m/s, and range from 1500 to 2800 m/s for the next lower layer. Calculated velocities are within acceptable ranges for near-surface sand, gravel, and clay bodies (Reynolds 1997). The lowest layer of the three-layer seismic case include a refractor around 30 m in depth. The velocities derived for the third layer are 2019 m/s and 4,444 m/s, which are reasonable value for bedrock velocity.

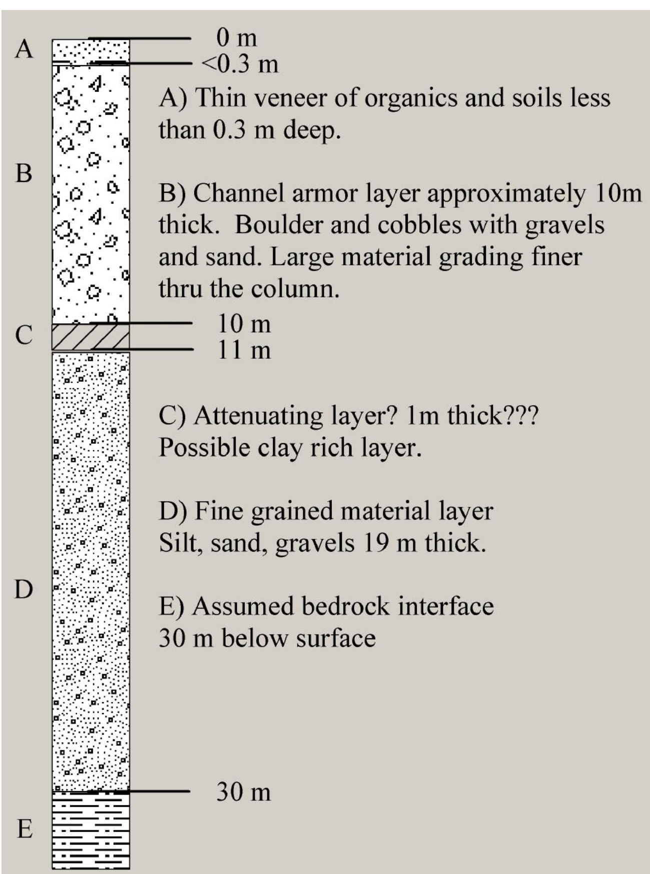
Both GPR and seismic had strong returns occurring in each survey line around 30 m below the surface. The agreement of this layer between GPR images suggests lateral continuity of the strong bedrock reflection, both in the area of high survey concentration and at those survey lines farther west and south (Philip 2004). There is a 1-m change in elevation of the GPR reflector over distances less than 40 m, indicating that reflection occurring as result of interaction with the water table is unlikely, because the slope is too steep for a water table surface (Philip 2004). Field observations in the Old Situk River Notch show evidence of perched water tables within the first few meters of the surface that were not identified on the GPR images because these surfaces were located within the noisy (ground-coupling) zone.

At this point the remotely sensed images are uncalibrated, since no drilling data were collected concurrent with the geophysical surveys. Stratigraphic interpretation is speculative at this time until actual drill data are collected at the Old Situk River control. These preliminary interpretations should not be solely used to make a final determination on terminal moraine or lake control stability. This determination will require a more intensive geotechnical investigation. The general stratigraphic interpretation provided (Figure 13) is based on current data obtained from field observations, geophysical surveys and research literature.

Layer A (0 - 0.3 m) (Figure 13) is the organic and soils layer, containing forest duff, minor soil development and root mass; Layer B (0.3 - 10-12 m below surface) consists of sediments ranging in size from sand to boulders with large boulder present at an 8 m depth; Layer C (10 - 11 m or possibly greater) is interpreted as a clay-rich layer; Layer D (11- ~30 m) is composed of unconsolidated silt, sand, and gravel; and Layer E (30 m or greater) is interpreted as bedrock.

This stratigraphic interpretation is similar to the general pattern mapped in an exposure 10 km northeast of the Old Situk River control by King (1995). No bedrock was found in that particular stratigraphic section, however bedrock was observed in a waterfall on the northwest portion of the terminal moraine along with suspected bedrock ridges (not verified in the field) along the southeastern portion of the terminal moraine. Also, 14 km downstream from the Old Situk River control the depth to bedrock was 64 m below the surface, supporting the bedrock interpretation at 30 m below the surface from the GPR reflections and seismic refractions.

Figure 13. Interpreted stratigraphic column at Old Situk River control. (Modified from Philip 2004).



Conclusions

Based on the current body of work, we have addressed the following questions:

1. Will all flow from newly formed Russell Lake flow into the Situk River?

The recent modeling work assuming rigid channel boundaries indicates the Old Situk River has the capacity of 7,100 cms before flowing into the Situk Lake overflow. This is 1.6 times the 100-year flood which is assumed close to a 500-year event. If the Old Situk channel were to become clogged with icebergs, water may elevate to a point where some spillover occurs. It is anticipated that most ice will pass through the Old Situk River control or ground out before entering the channel.

2. If flooding occurs, what are the risks to the community and existing infrastructure?

All hydraulic modeling from the recent studies indicates minor impacts on the Yakutat airport area. However, the uncertainty related to debris dams formed during initial overflow or long term lateral migration of the new Situk channel would increase the risk to the airport. These risks can be mitigated by revetment protecting the airport (Miles 2004). All cabins or improvements along the Situk River would be lost during the initial flood.

3. Are the 1986 flow and floodplain assessments valid?

Results from recent work indicate slightly wider inundated areas and water levels than the 1986 study. The recent work indicates low lying portions of the airport could see some inundation at peak flow events. Elevations for the Old Situk River control determined by the 1986 study are within an acceptable margin of error from those determined by the 2002 surveying and LIDAR terrain modeling.

4. Is it feasible and by what method could Russell Lake overflow be diverted into another drainage system?

Additional studies are required to determine feasibility of a channel diversion. The Forest Service and Corps of Engineers (COE) are in the planning stages of a feasibility study, however the moraine stability study is required before feasibility assessment can commence.

5. Is the terminal moraine at the lake outlet stable?

Since flows will be larger than the previous channel forming flows, we anticipate that channel will laterally scour: To what extent is uncertain without additional geotechnical drilling and remotely sensed subsurface data. Additional work is scheduled in 2005.

6. Will the ice dam forming Russell Lake be persistent and stable at the next closure?

At this point in time we do not know when the glacier will close off. An ice stability study is in the planning stages by the COE.

Future Work

Additional work is needed to examine the stability of the terminal moraine and other lake outlet controls, moraine/ice-dam permanence, and feasibility of a diversion channel to protect the economic integrity of the City of Yakutat. Currently the USDA Forest Service is the lead agency in charge of the project. A memorandum of agreement is being negotiated between the Forest Service and the Army Corps of Engineers (COE) to determine the feasibility of constructing a diversion channel and assessing the stability of the Hubbard Glacier ice dam and moraine.

Ice-Dam Stability

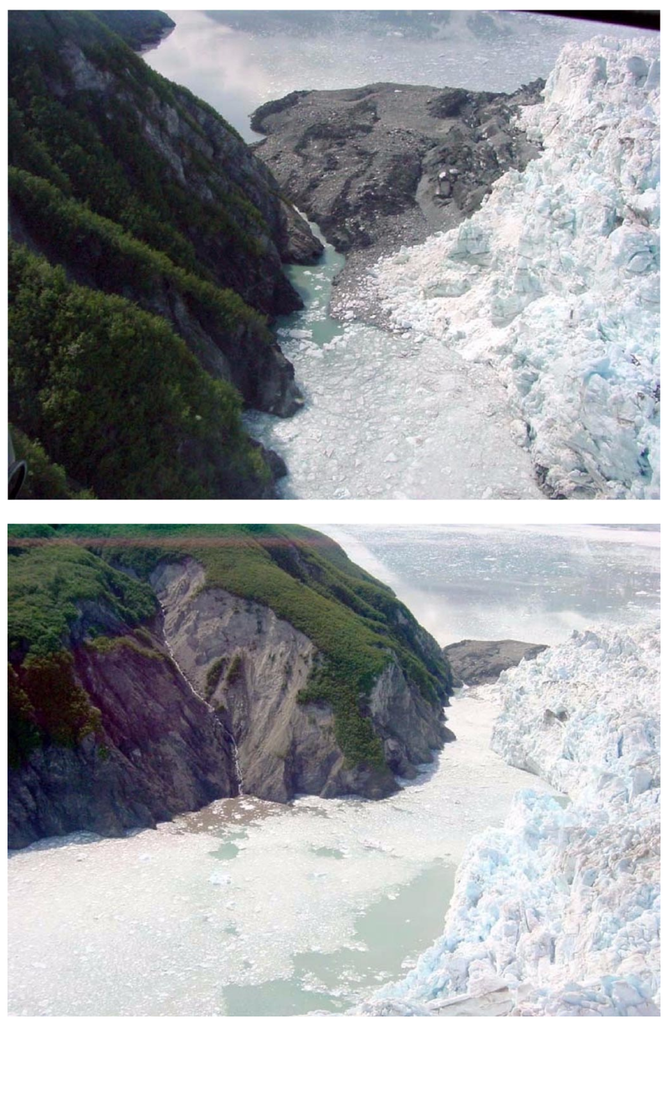
Understanding moraine and ice dam stability is an important consideration before expending large amounts of capital for a diversion project. The 1986 and 2002 damming events were relatively short lived (~3 months) and the configurations of each dam were different. The 1986 ice dam was made almost entirely of ice with small moraines at the edges. The 2002 dam was primarily composed of sediment accumulating in front of the glacier, forming a large terminal push moraine (Figure 14) that continued to build at the same rate the lake level increased. The 1986 and 2002 dams also failed in different manners. The 1986 ice dam experienced a structural failure with rapid calving around the seaward glacier face just before the ice dam broke apart. The 2002 moraine and ice dams failed when the lake overtopped and rapidly eroded the moraine, causing the dam to fail. The moraine dam was overtopped when a storm caused lake level to rise 1.5 m in two days, exceeding the growth rate of the moraine. The formation and failure mechanisms for each of these glacier dams are extremely complex, but provide the important variables that need to be considered when assessing future occurrences and developing mitigation measures.

Ice dam stability is a function of: 1) sediment accumulation around the dam, which reduces the amount of calving; 2) mass of the dam (thickness and height); 3) hydrostatic pressure in the lake, which determines the force acting on the dam and flotation of the dam; 4) bed topography and composition beneath the dam, which determines glacier mobility and subglacial outflow; 5) degree of ice fracturing and interconnectedness of the crevasse system, which determines englacial outflow; and 6) the rate of glacier advance. To better address ice dam stability, additional data will need to be collected that includes bathymetry to monitor sediment accumulation, subacoustic profiling to determine sediment thickness and bed topography, and full waveform LIDAR to characterize the crevasse system. Data collection is currently being planned and will begin in 2005 if funding is available.

Moraine and Lake Control Stability

To address public safety issues from moraine failure or catastrophic incision of the Old Situk River control spillway during large storm events, additional geophysical analysis and geotechnical drilling are required. The USFS and COE are developing plans to collect and assess this data in 2005. Geotechnical drilling, GPR and seismic surveys will be used to characterize the materials (size, composition, distribution, and permeability) of the Russell moraine in order to model the response of those materials to extreme events.

Figure 14. Oblique aerial view of 2002 moraine dam and outflow channel from Russell Fiord. (a) Entire moraine dam and overflow channel; (b) Ice choked channel with glacier face and dam.



Diversion Feasibility

An overflow of Russell Lake into the Situk River will have severe immediate economic consequences to the Yakutat economy, which is almost entirely driven by commercial and recreational fishing on the Situk River. At the request of the City of Yakutat, Alaska congressional delegation, and the Governor's office, the USFS and COE will perform a study to assess the feasibility of constructing a diversion channel. Preliminary work identified several diversion options including: 1) constructing a narrow trench in which the stream is allowed to erode and develop into a self formed channel; 2) designing and constructing a 16.3-km channel from the terminal moraine to the ocean; and 3) boring a 4.8-km diversion tunnel through the mountains that divide Yakutat Bay from Russell Fiord. The magnitude and extremely high costs of a project of this scope warrant a thorough and detailed assessment to determine the feasibility of the different diversion options. The diversion feasibility study will involve design and layout of various channel options, hydraulic modeling of flood events in the new proposed locations, and improved cost estimation. The work will commence in 2005 if funding is available.

Acknowledgements. We would like to thank Mark Miles (Alaska Department of Transportation), Ed Neal (USGS), Noel Philip (University of Montana), and Roman Motyka (University of Alaska) for your expertise, and analyses conducted in this ongoing effort; The Yakutat District Ranger Patricia O'Connor and her staff, for all their help and continued effort in assisting and facilitating this work; and Dan Cenderelli and Jerome DeGraff for review and constructive comments on this paper.

Photo credits: All photos were taken by Tongass National Forest employees during the course of their work.

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