

CHAPTER 3. REGION

Bristol Bay is a large gulf of the Bering Sea located in southwestern Alaska. The land area draining to Bristol Bay consists of six major watersheds—from west to east, the Togiak, Nushagak, Kvichak, Naknek, Egegik, and Ugashik River watersheds—and a series of smaller watersheds draining the North Alaska Peninsula (Figure 2-3). The Bristol Bay region encompasses complex combinations of physiography, climate, geology, and hydrology, which interact to control the amount, distribution, and movement of water through a landscape shaped by processes such as tectonic uplift, glaciation, and fluvial erosion and deposition. The region's freshwater habitats are varied and abundant, and support a diverse and robust assemblage of fish (Chapter 5).

The Nushagak and Kvichak River watersheds account for more than half the land area in the Bristol Bay watershed (Table 2-1). The Pebble deposit, the largest known porphyry copper deposit in the region, is located in the headwaters of both watersheds (Figure 2-4) and represents the most likely site for near-term, large-scale mine development in the Bristol Bay watershed. In this chapter, we consider key aspects of the Bristol Bay watershed's physical environment, with particular emphasis on the Nushagak and Kvichak River watersheds (Figure 2-4).

3.1 Physiographic Divisions

The Nushagak and Kvichak River watersheds comprise five distinct physiographic divisions (Wahrhaftig 1965): the Ahklun Mountains, the Southern Alaska Range, the Aleutian Range, the Nushagak–Big River Hills, and the Nushagak–Bristol Bay Lowland (Table 3-1, Figure 3-1). Precipitation is greatest in the Southern Alaska Range, the Aleutian Range, and the Ahklun Mountains (Figures 3-1 and 3-2), and these physiographic divisions serve as major water source areas for lower portions of the watersheds. Annual water balance, especially in the mountains and hills, is dominated by snowpack accumulation and subsequent melt, although late summer and fall rains are also important contributors to the hydrologic cycle, particularly in the Nushagak–Bristol Bay Lowland division (Selkregg 1974). Additional key attributes of each physiographic division are discussed below.

The Ahklun Mountain physiographic division, in the western portion of the Nushagak River watershed, is dominated by rolling hills to sharp, steep, glaciated mountains that receive high snowfall (Table 3-1, Figure 3-1) (Wahrhaftig 1965, Selkregg 1974, Gallant et al. 1995). Parent bedrock is deformed sedimentary rocks, intruded in several locations by igneous batholiths and stocks (Figure 3-3). A few small glaciers occur in high mountain cirques, and isolated masses of permafrost occur sporadically (Figure 3-4). Glacially carved lowland valleys are now filled with large, deep lakes, and adjacent streams are often incised in bedrock gorges. The surrounding area is mantled with colluvium, alluvium, and glacial drift and moraines (Figure 3-3). Soils are generally well drained and have medium erosion potential (Figures 3-5 and 3-6). Dwarf scrub is the dominant vegetation in the mountains and tall scrub and herbaceous plants are common in the valleys and lower mountain slopes (Figure 3-7).

The Southern Alaska Range physiographic division comprises a series of high, steep, glaciated mountains with land surfaces covered by rocky slopes, glacial drift and moraines, and glaciers (Table 3-1, Figure 3-1) (Wahrhaftig 1965, Selkregg 1974). Bedrock is a complex of granitic batholiths intruded into metamorphosed sedimentary and volcanic rock (Figure 3-3). Soils are shallow or not present (Figure 3-5) and permafrost occurs as isolated masses (Figure 3-4). Alpine tundra is the predominant vegetation (Figure 3-7). Streams are frequently swift and braided with several headwaters originating in glaciers (Figure 3-8). Several large, deep lakes occur in the glaciated valleys within the division (Figure 3-8). Braided, turbid streams flow into lakes, allowing sediment to settle, before flowing into the Nushagak and Kvichak River systems.

Within the Bristol Bay watershed, the Aleutian Range physiographic division consists of rolling hills to steep, glaciated mountains built of sedimentary, volcanic, and intrusive bedrock (Table 3-1, Figure 3-1) (Wahrhaftig 1965, Selkregg 1974). Cirque glaciers remain atop mountains in the extreme southeast corner of the Kvichak River watershed (Figure 3-3). This division is generally free of permafrost (Figure 3-4). Soils have formed in volcanic ash over glacial deposits at lower elevations, whereas rocky lands dominate at higher elevations (Figure 3-5). Erosion potential is high for some soils in the Aleutian Range division (Figure 3-6). Large, deep, moraine- and sill-impounded lakes are found in the ice-carved valleys. The Alagnak River, which drains most of the Aleutian Range physiographic division within the Bristol Bay watershed, is highly braided as it flows across the Nushagak–Bristol Bay Lowland division to the Kvichak River. Dwarf scrub vegetation is common (Figure 3-7) (Selkregg 1974, Gallant et al. 1995).

Table 3-1. Physiographic divisions (Wahrhaftig 1965) of the Nushagak and Kvichak River watersheds.

Physiographic Division	Description	Elevation (meters)	Permafrost Extent	Freshwater Habitats
Ahklun Mountains	Rolling hills to sharp, steep, glaciated mountains separated by broad lowlands, with a few small glaciers in high mountain cirques	10–1,600	Sporadic	Mix of unconstrained and constrained streams; Wood and Tikchik Lakes in U-shaped valleys
Southern Alaska Range	Rolling hills to steep, glaciated mountains covered by glacial drifts and moraines, rocky slopes, and glaciers	14–2,800	Unknown	Swift, braided streams and rivers, some with glacial headwaters; Lake Clark and other large lakes in glaciated valleys
Aleutian Range	Rolling hills to sharp, steep glaciated mountains, separated by broad lowlands, with a few small glaciers in high mountain cirques	14–1,600	Unknown	Large lakes associated with ice-carved valleys and terminal moraines; glacially fed lake tributaries
Nushagak–Big River Hills	Rounded ridges with broad, gentle slopes and broad, flat or gently sloping valleys	14–1,300	Sporadic	Glacial moraines and ponds in eastern part of region; upper reaches of the Nushagak and Mulchatna Rivers
Nushagak–Bristol Bay Lowland	Flat to rolling landscape with low local relief and deep morainal, drift, and outwash deposits, but no glaciers	0–800	Sporadic or absent	Morainal and thaw lakes; western half of Iliamna Lake; Kvichak, Alagnak, Nushagak, Nuyakuk, and Mulchatna River mainstems

Figure 3-1. Hydrologic landscapes within the Nushagak and Kvichak River watersheds, as defined by physiographic division and climate class. Physiographic divisions (Wahrhaftig 1965) are classified as Ahklun Mountains, Nushagak–Bristol Bay Lowland, Aleutian Range, Nushagak–Big River Hills, and Southern Alaska Range. Climate classes (Feddema 2005) were defined as very wet, wet, moist, dry, and semiarid, and calculated using 30-year (1971–2000) mean annual precipitation averages from the Scenarios Network for Alaska and Arctic Planning data (SNAP 2012). Points labeled A through H indicate approximate locations where photos in Figure 3-8 were taken.

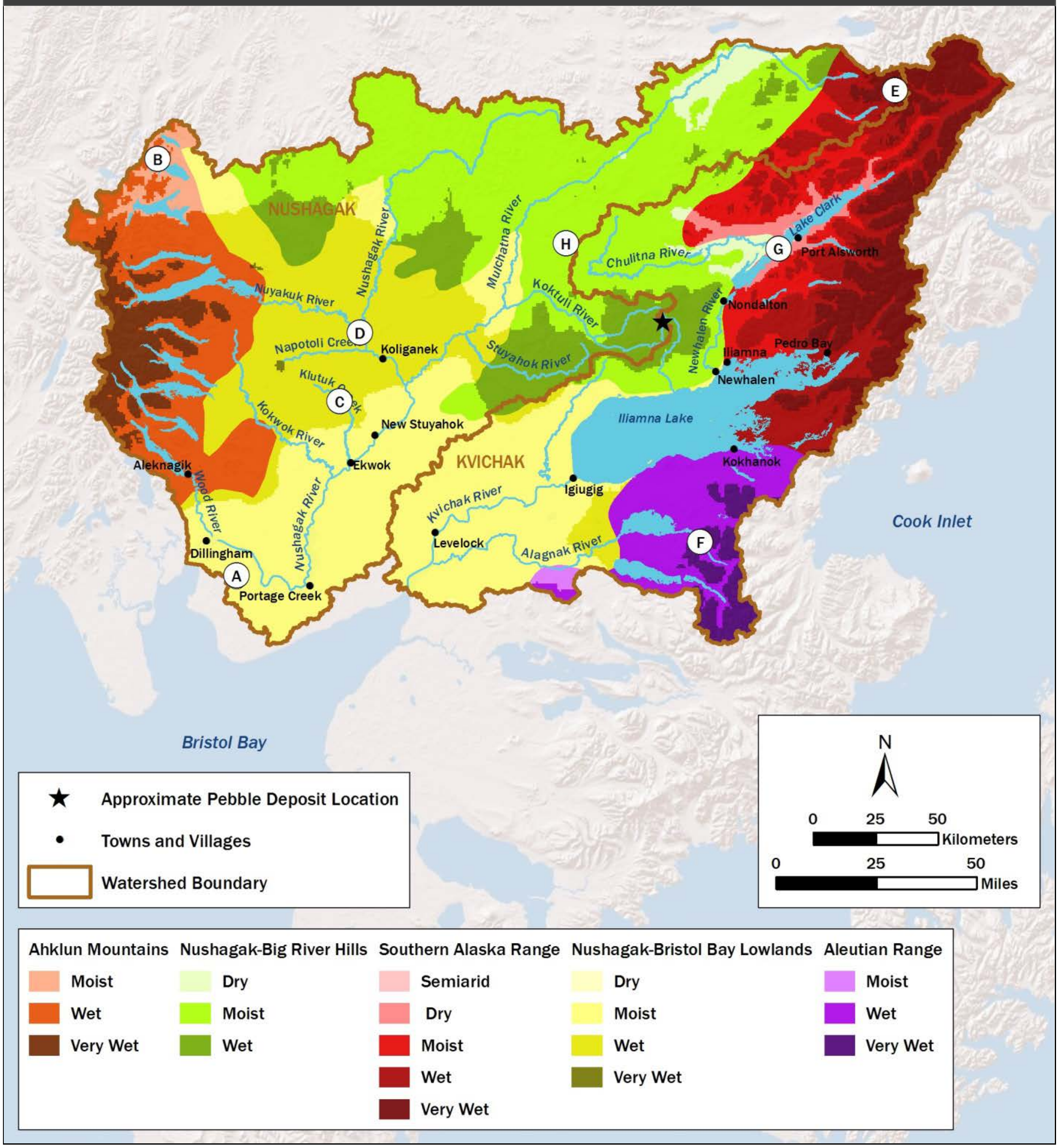


Figure 3-2. Distribution of mean annual precipitation (mm) across the Nushagak and Kvichak River watersheds, 1971 to 2000 (SNAP 2012).

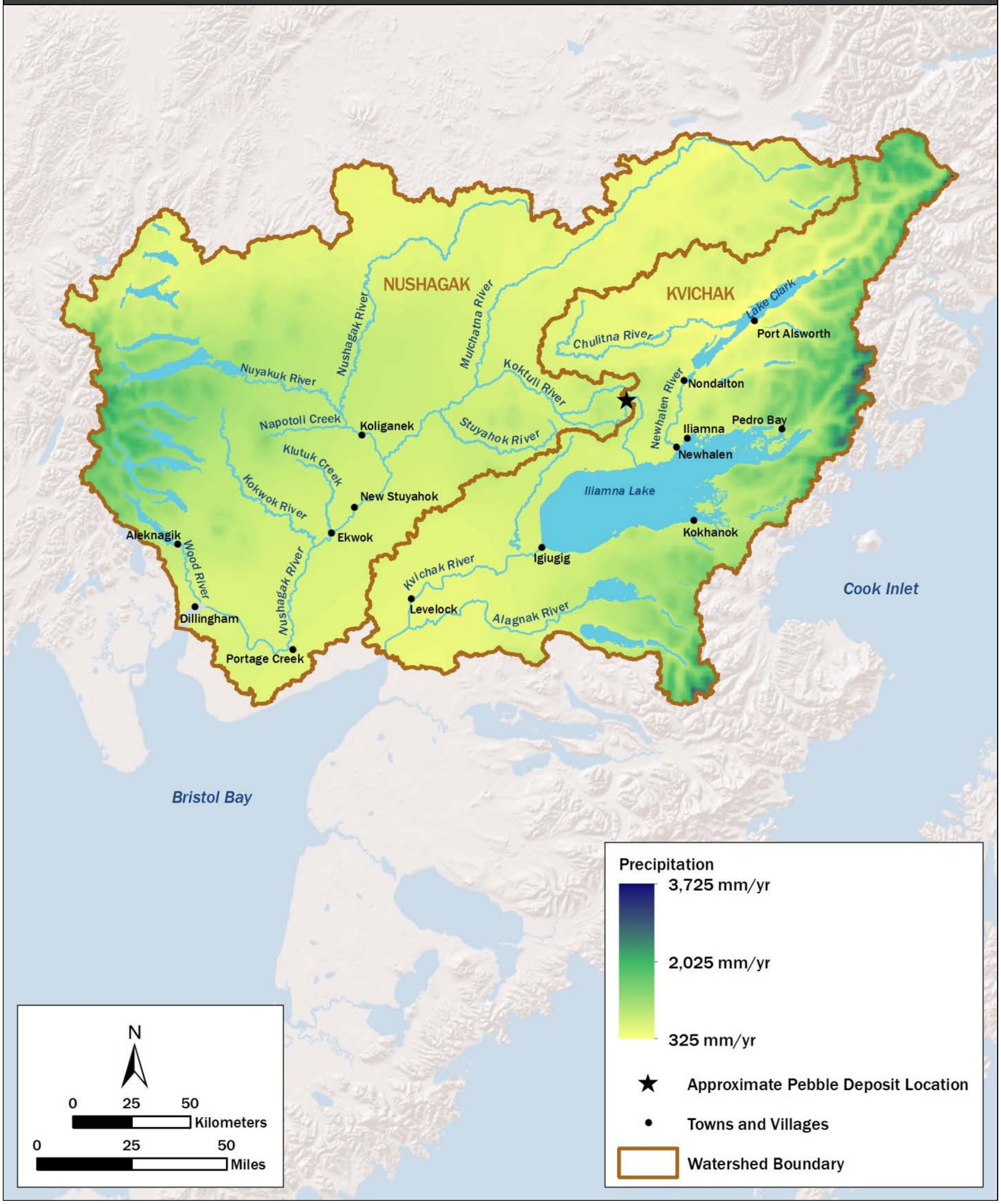


Figure 3-3. Generalized geology of the Bristol Bay watershed (adapted from Selkregg 1974).

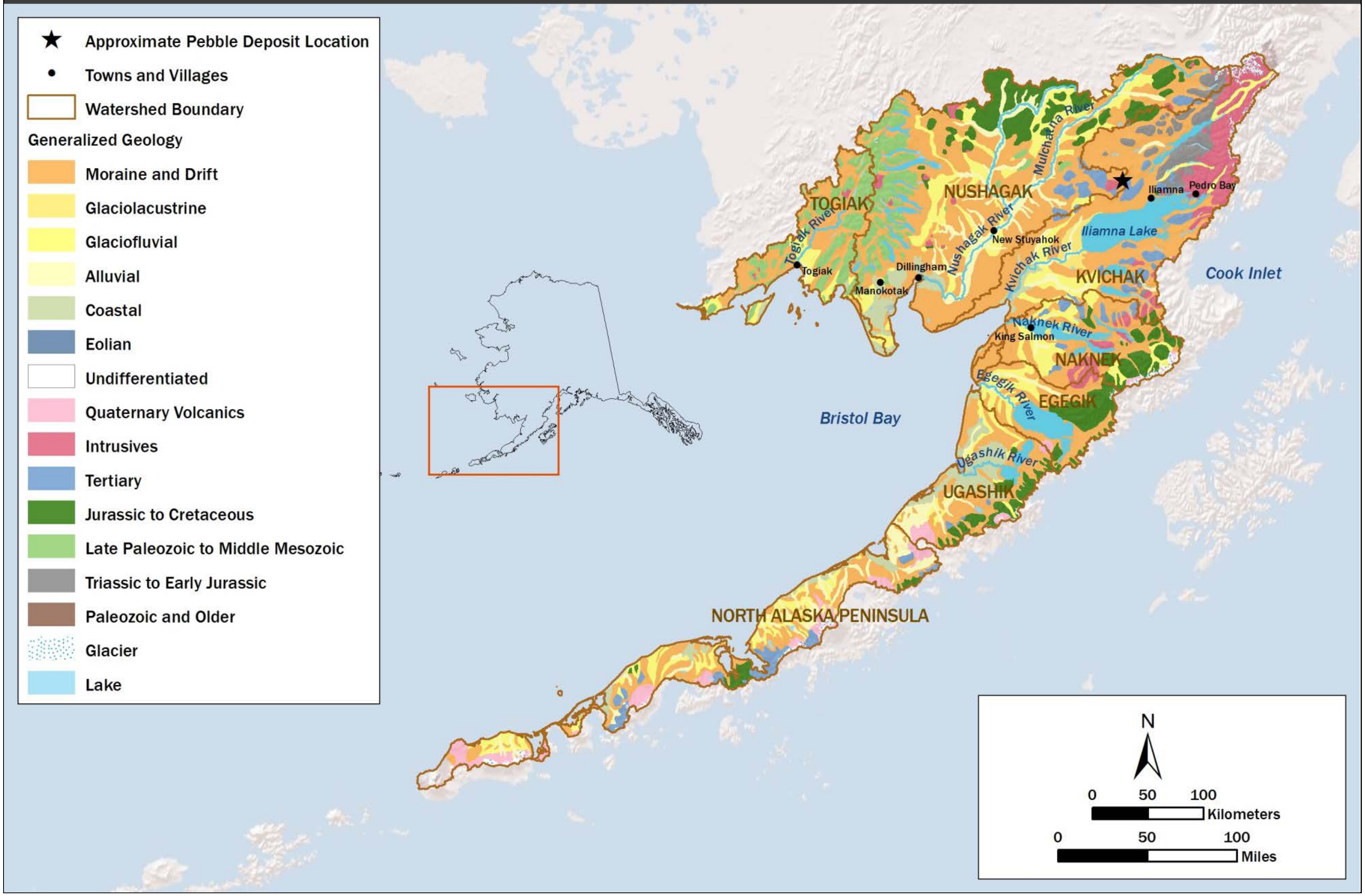


Figure 3-4. Occurrence of permafrost in the Bristol Bay watershed (adapted from Selkregg 1974).

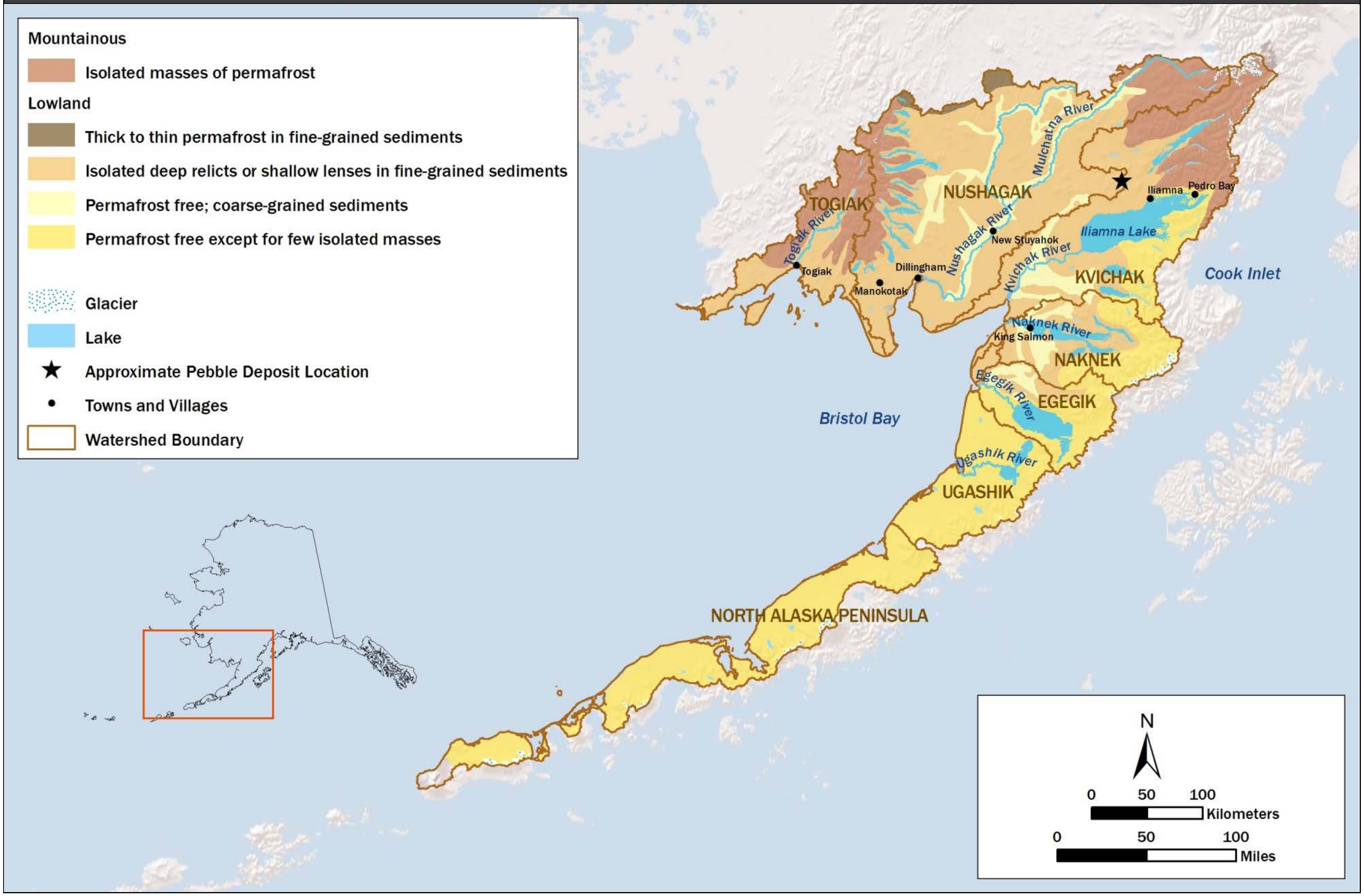


Figure 3-5. Dominant soils in the Bristol Bay watershed (adapted from Selkregg 1974).

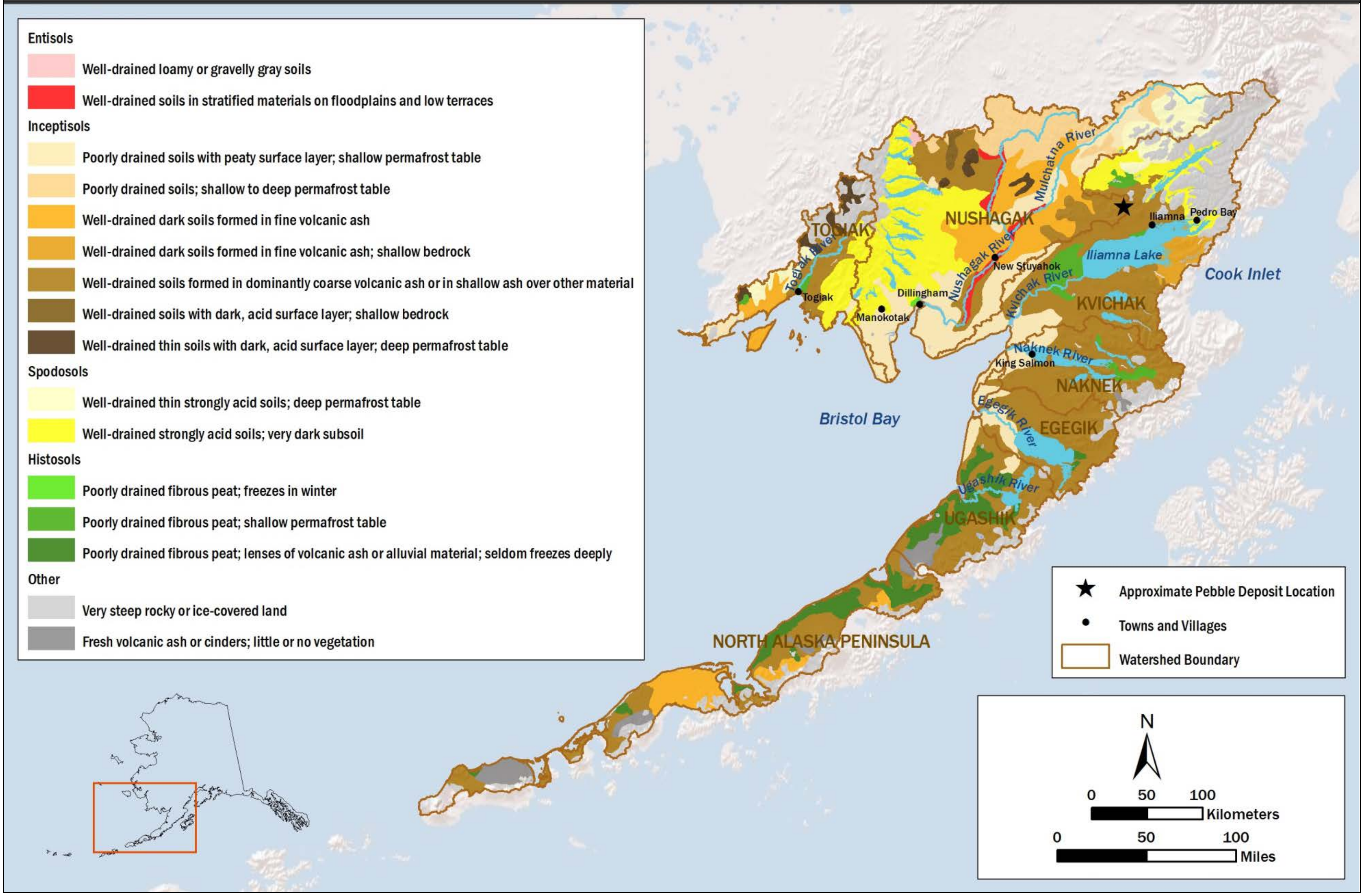


Figure 3-6. Erosion potential in the Bristol Bay watershed (adapted from Selkregg 1974).

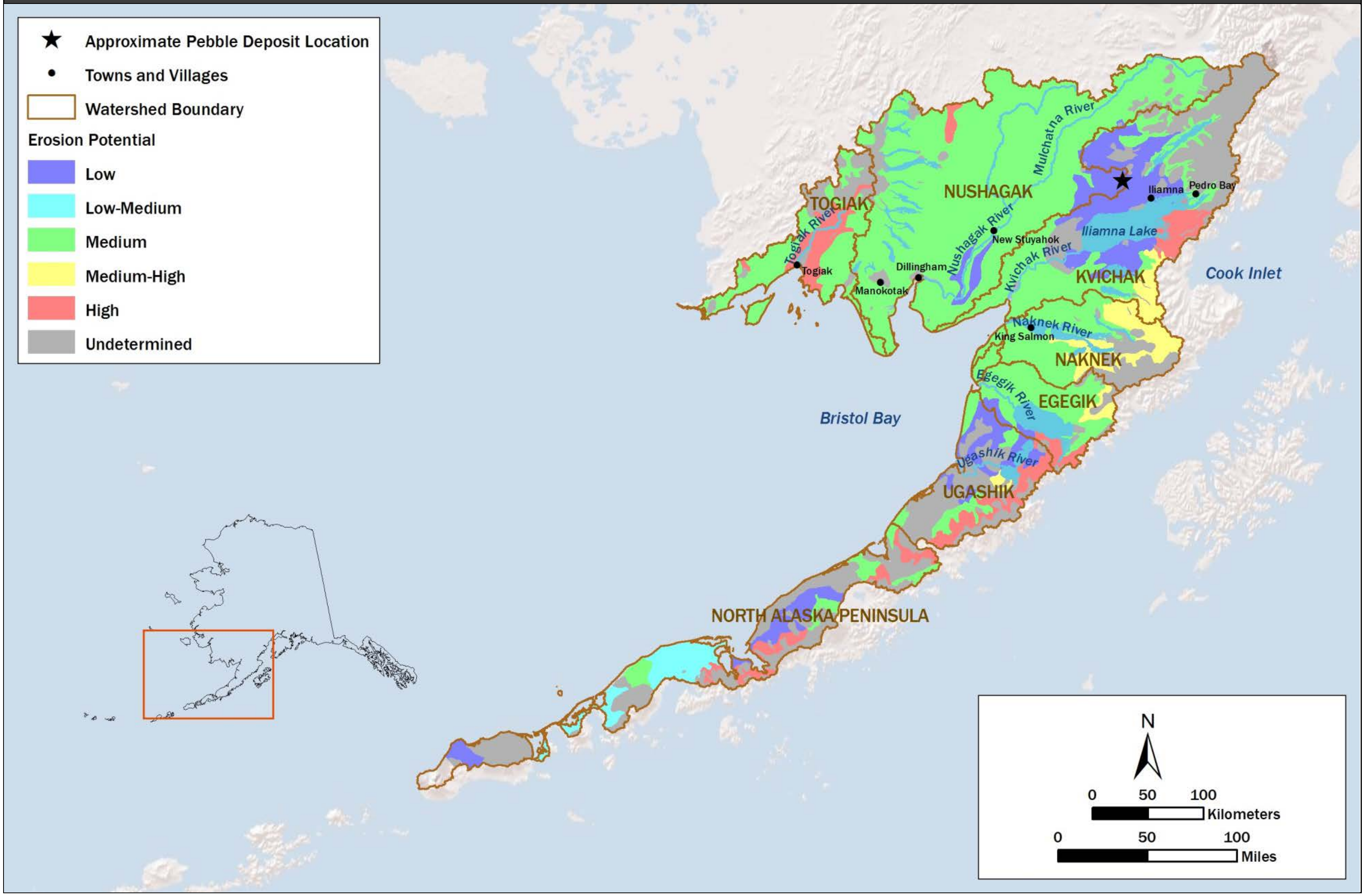


Figure 3-7. Dominant vegetation in the Bristol Bay watershed (adapted from Selkregg 1974).

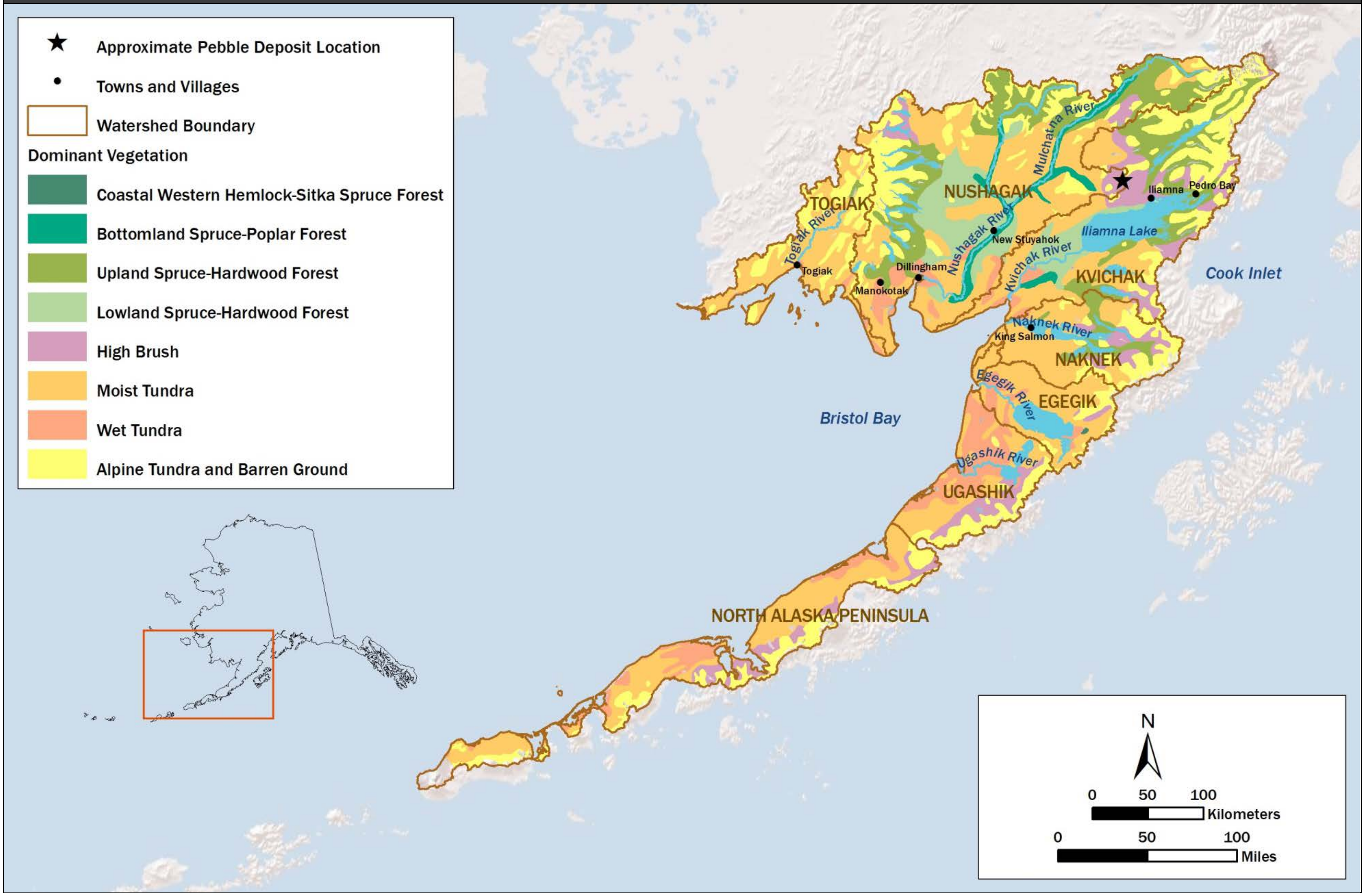
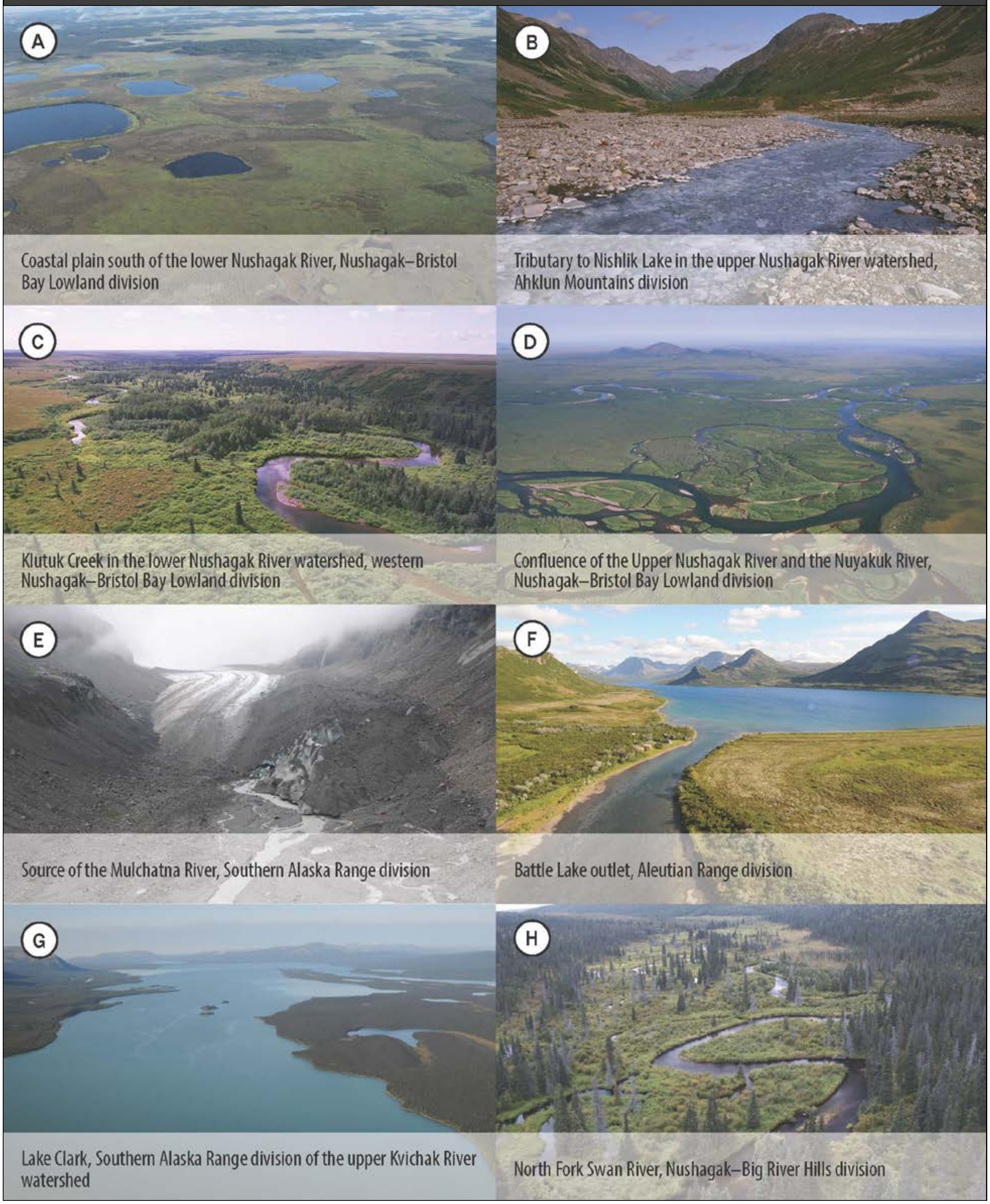


Figure 3-8. Physiographic divisions of the Nushagak and Kvichak River watersheds of Bristol Bay. The Nushagak and Kvichak River watersheds contain a wide range of aquatic habitats within five distinct physiographic divisions; see Figure 3-1 for a map of these divisions and the general location where each photo was taken. All photos taken between August 2003 and August 2013, courtesy of Michael Wiedmer.



The Nushagak–Big River Hills physiographic division consists largely of rounded ridges that have moderate elevations and broad, gentle slopes and broad, flat or gently sloping valleys (Table 3-1, Figure 3-1) (Wahrhaftig 1965, Selkregg 1974). Major geologic formations include graywacke, argillite, conglomerate, and greenstone flows (Figure 3-3). No modern glaciers are present, but glacial drift and moraines are common throughout lower elevations and colluvium and alluvium mantle higher elevations. The Nushagak River headwaters are the only part of the Nushagak and Kvichak River watersheds that have not been glaciated. In most of this division falling within the Nushagak and Kvichak River watersheds, permafrost is found only in isolated masses or lenses (Figure 3-4). Soils throughout the division are typically shallow, occur in well-drained to poorly drained conditions, and have medium erosion potential (Figures 3-5 and 3-6). Rivers in the Mulchatna and Newhalen River systems originate from glaciers in the Southern Alaska Range. Sediment from these glaciers is trapped in large lakes, providing clearer water for downstream reaches.

The Pebble deposit is located in the eastern portion of the Nushagak–Big River Hills and is heavily influenced by past glaciation (PLP 2011: Chapter 3). At various times, Pleistocene glaciers blocked the South Fork Koktuli River, the North Fork Koktuli River, and Upper Talarik Creek, the three tributaries draining the Pebble deposit area (Figure 2-5). Unconsolidated glacial deposits, ranging from a few to several tens of meters in thickness, cover most of the area's lower elevations (Detterman and Reed 1973). All three of the stream valleys in the Pebble deposit area have extensive glacial sand and gravel deposits (PLP 2011: Chapter 8). Based on studies in the Pebble area, the Pebble Limited Partnership (PLP) (2011) concluded that the presence of permeable shallow aquifers, upward hydraulic gradients, and strong local relief indicate that local and intermediate groundwater flow systems dominate regional groundwater flow systems. Further, PLP (2011) noted the presence of many local, cross-cutting faults with high hydraulic conductivities in the Pebble deposit area.

The Nushagak–Bristol Bay Lowland physiographic division (Table 3-1, Figure 3-1) is mantled with glacial drift and moraine deposits up to hundreds of meters deep, forming a rolling landscape with low local relief (15 to 75 m) and maximum elevations of 90 to 150 m near the transitions from the lowland to adjacent mountains or hills (Wahrhaftig 1965, Detterman 1986, Lea et al. 1991, Stilwell and Kaufman 1996). Arc-shaped bands of morainal deposits ranging from 1.6 to 8 km wide enclose Iliamna Lake and are frequent in the lowlands between the Nushagak River and the Ahklun Mountains division (Figure 3-3). Steep outliers of the Wood River Mountains in the Ahklun Mountains physiographic division arise from the western part of the lowland. A small area with sand dunes occurs east of the Nushagak River (Lea and Waythomas 1990). Glacial drift is coarser near the mountains because of high amounts of outwash and grades to fine sand along the coast (Wahrhaftig 1965). The remainder of the lowland is dominated by low-relief (less than 20 m), rolling expanses of tundra underlain by Holocene peat and wind-born deposits (Lea et al. 1991). Glaciers do not occur today in the Nushagak–Bristol Bay Lowland division, and permafrost is sporadic or absent (Figure 3-4) (Wahrhaftig 1965). Morainal and thaw lakes are common, and mainstem rivers draining this area exhibit high channel complexity (Figure 3-8). Poorly drained soils dominate in the southern portions, whereas well-drained soils dominate across the remainder of the physiographic division (Figure 3-5). Soil erosion potential is moderate throughout the area (Figure 3-6). Extensive dwarf scrub communities occur on relatively well-drained soils, and moist and wet tundra communities cover large areas as well (Figure 3-7) (Selkregg 1974, Gallant et al. 1995).

3.2 Hydrologic Landscapes

To better evaluate the influence of inherent river basin attributes on streamflows and thus fish populations, we used the physiographic divisions discussed above to define different hydrologic landscapes across the Nushagak and Kvichak River watersheds. These landscapes can be considered hydrologic building blocks, in that they provide a broad-scale approach to spatially characterizing climate and watershed factors controlling the amount, timing, and flowpaths of water within the watersheds (Winter 2001).

We defined hydrologic landscapes by calculating water surplus (precipitation minus potential evapotranspiration) across the basins in each of the five physiographic divisions, using Scenarios Network for Alaska and Arctic Planning (SNAP) data (SNAP 2012) and procedures outlined by Feddema (2005). Feddema (2005) defined six annual climate classes ranging from very wet to arid conditions. The very wet, wet, and moist classes have an annual water surplus, whereas the dry, semi-arid, and arid classes have an annual water deficit. Combining these climate classes with the physiographic divisions (Section 3.1), we identified 18 different hydrologic landscapes across the Nushagak and Kvichak River watersheds (Table 3-2, Figure 3-1), which represent the range of hydrologic characteristics across the region.

3.3 Groundwater Exchange and Flow Stability

A key aspect of the Bristol Bay watershed's aquatic habitats is the importance of groundwater exchange. Because salmon rely on clean, cold water flowing over and upwelling and downwelling through porous gravels for spawning, egg incubation, and rearing (Bjornn and Reiser 1991), areas of groundwater exchange create high-quality salmon habitat (Appendix A). For example, densities of beach spawning sockeye salmon in the Wood River watershed were highest at sites with strong groundwater upwelling and zero at sites with no upwelling (Burgner 1991). Portions of the Nushagak–Bristol Bay Lowland and Nushagak–Big River Hills physiographic divisions, including the Pebble deposit area, contain coarse-textured glacial drift with abundant, high-permeability gravels and extensive connectivity between surface waters and groundwater (Figures 3-3, 3-4, and 3-9). Abundant wetlands and small ponds also contribute disproportionately to groundwater recharge (Rains 2011). This strong connection between groundwater and surface waters helps to moderate water temperatures and streamflows. For example, groundwater contributions that maintain water temperatures above 0^{0}C are critical for maintaining winter refugia in streams that might otherwise freeze (Power et al. 1999).

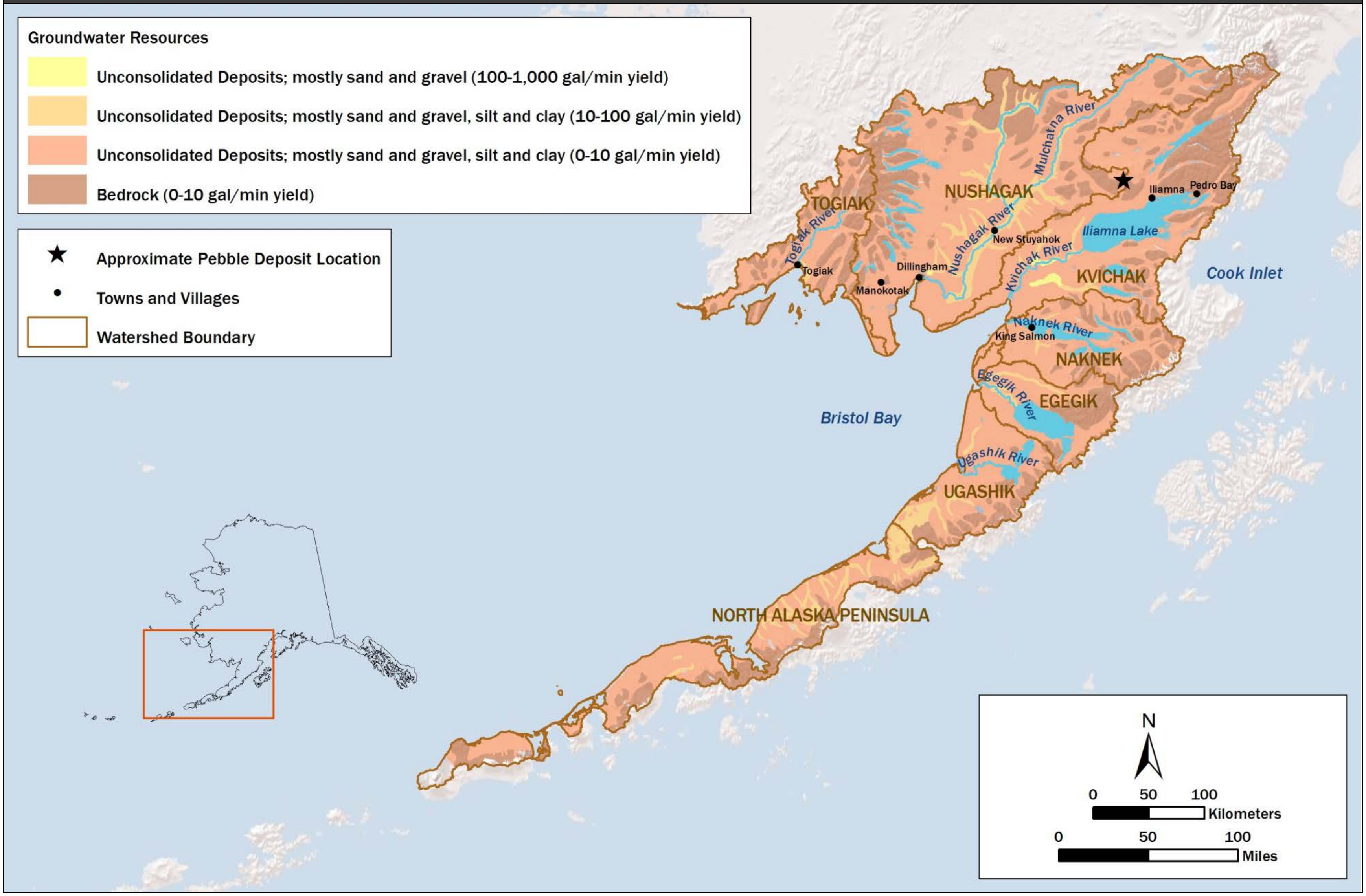
Table 3-2. Distribution of hydrologic landscapes in the Nushagak and Kvichak River watersheds. Values represent percentage of total area in the two watersheds.

Physiographic Division	Ahklun Mountains			Southern Alaska Range				Aleutian Range			Nushagak–Big River Hills				Nushagak–Bristol Bay Lowland		
Climate Class	V	W	M	V	W	M	D	V	W	M	V	W	M	D	V	W	M
Nushagak River Watershed																	
Nushagak River (whole watershed)	7	16	1	1	2	-	-	-	-	-	-	25	9	-	-	24	15
Nushagak River at Ekwok[a]	4	9		2	3	-	-	-	-	-	-	40	14	-	-	27	1
Nuyakuk River	19	43	2			-	-	-	-	-	-	3			1	32	-
Mulchatna River				4	7	-	-	-	-	-	-	53	22	-	-	14	-
Nushagak River at Mulchatna River	8	18	1	-	-	-	-	-	-	-	-	30	9	-	-	35	-
Koktuli River	-	-	-	-	-	-	-	-	-	-	-	99	-	-	-	1	-
South Fork Koktuli River[b]	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	-	-
North Fork Koktuli River[c]	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	-	-
Kvichak River Watershed																	
Kvichak River (whole watershed)	-	-	-	16	13	8	1	2	11	2	-	7	7	-	-	3	28
Kvichak River at Igiugig[d]	-	-	-	25	20	12	2	-	-	6	-	10	11	1	-	-	11
Kaskanak Creek near Igiugig[e]	-	-	-	-	-	-	-	-	-	-	-	21	-	-	-	28	50
Iliamna River near Pedro Bay[f]	-	-	-	94	6	-	-	-	-	-	-	-	-	-	-	-	-
Upper Talarik Creek[g]	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	-	-

Notes:
Dashes (-) indicate hydrologic landscapes that are not found in that portion of the Nushagak or Kvichak River watersheds. Climate classes are defined as very wet (V), wet (W), moist (M), and dry (D) according to Feddema (2005); no semi-arid or arid climates are found in the region.

[a] USGS gage 15302500.
[b] USGS gage 15302200.
[c] USGS gage 15302250.
[d] USGS gage 15300500.
[e] USGS gage 15302520.
[f] USGS gage 15300300.
[g] USGS gage 15300250.

Figure 3-9. Groundwater resources in the Bristol Bay watershed (adapted from Selkregg 1974). Yields are presented in gallons per minute.



These groundwater contributions to streamflow, along with the influence of large and small lakes, support flows in the region's streams and rivers that are more stable than those typically observed in many other salmon streams (e.g., in the Pacific Northwest or southeastern Alaska). Greater groundwater contributions to streams result in more moderated streamflow regimes with lower peak flows and higher base flows, creating a less temporally variable hydraulic environment. The lower mainstem Nushagak and Kvichak Rivers illustrate this tendency toward moderated, consistent streamflows (Figure 3-10). Coarse-textured glacial drift in the Kaskanak and Upper Talarik Creek drainages promotes high groundwater contributions to these streams, resulting in stable flows through much of the year (Figure 3-10). High baseflow in the Nushagak River also is consistent with increased interactions between surface water and groundwater, as water flows from the Southern Alaska Range, Ahklun Mountains, and Nushagak–Big River Hills into the coarse-textured glacial drift of the Nushagak–Bristol Bay Lowland (Figure 3-10).

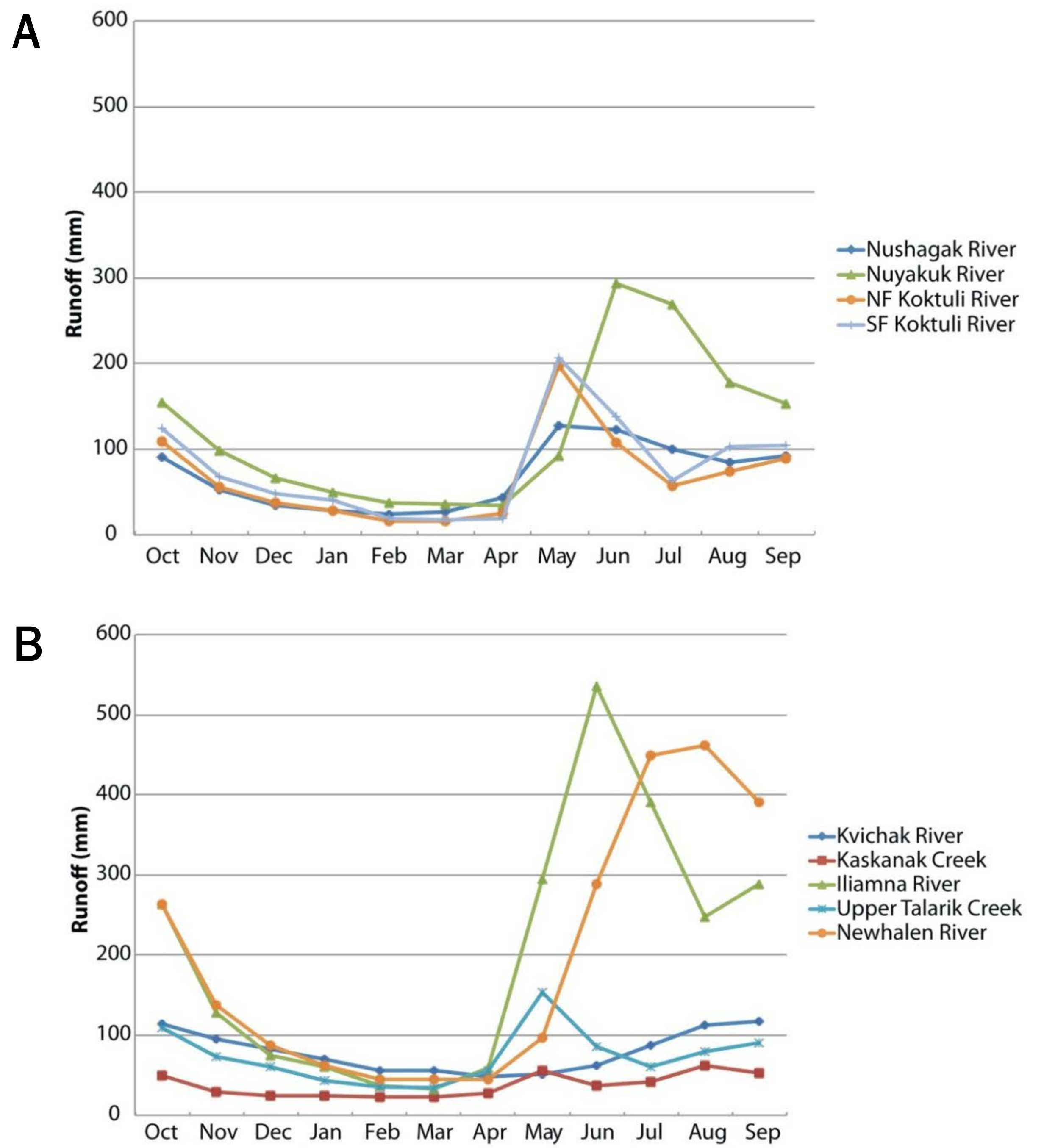
Water storage in upstream lakes plays a role in flow stabilization, as well. For example, in the Kvichak River watershed, Iliamna Lake dampens high flows from the Iliamna and Newhalen Rivers before they reach the mainstem. The attenuating effect of upstream lakes on streamflow is also evident in the Newhalen River, located downstream of Lake Clark (Figure 3-10).

3.4 Quantity and Diversity of Aquatic Habitats

Differences in hydrology, geology, and climate across the Bristol Bay watershed interact to create the region's diverse hydrologic landscapes (Table 3-2, Figure 3-1) and ultimately shape the quantity, quality, diversity, and distribution of aquatic habitats throughout the watershed. These diverse habitats, in conjunction with the enhanced ecosystem productivity associated with anadromous salmon runs, support a high level of biological complexity that contributes to the environmental integrity and resilience of the watershed's ecosystems (Schindler et al. 2010, Ruff et al. 2011, Lisi et al. 2013).

In general, conditions in the Bristol Bay watershed are highly favorable for Pacific salmon. The Nushagak and Kvichak River watersheds encompass an abundant and diverse array of aquatic habitats and support a diverse salmonid assemblage (Section 5.2). Freshwater habitats range from headwater streams to braided rivers, small ponds to large lakes, side channels to off-channel alcoves. These watersheds contain over 54,000 km of streams, 14% of which have been documented as anadromous fish streams (Johnson and Blanche 2012). This percentage is likely a significant underestimate of the actual extent of anadromous waters across the watersheds (Box 7-1, Appendix A).

Figure 3-10. Mean monthly runoff for selected streams and rivers in the Nushagak and Kvichak River watersheds. USGS gages and dates used to generate each line: A. Nushagak River watershed: Nushagak River (15302500, Oct 1977–Sep 1993); Nuyakuk River (15302000, Jun 1953–Sep 2010); North Fork (NF) Koktuli River (15302250, Sep 2004–Sep 2010); South Fork (SF) Koktuli River (15302200, Sep 2004–Sep 2010). B. Kvichak River watershed: Kvichak River (15300500, Aug 1967–Sep 1987); Kaskanak Creek (15300520, Jun 2008–Sep 2011); Iliamna River (15300300, Jun 1996–Sep 2010); Upper Talarik Creek (15300250, Sep 2004–Sep 2010); Newhalen River (15300000, Jul 1951–Sep 1986).



Lakes and associated tributary and outlet streams are key spawning and rearing areas for sockeye salmon. Lakes cover relatively high percentages of watershed area in the Bristol Bay region: 7.9% for the entire Bristol Bay watershed area and 13.7% for the Kvichak River watershed (RAP 2011). In other North Pacific river systems supporting sockeye salmon populations, from northern Russia to western North America, these values tend to be much lower (e.g., 0.2 to 2.9%) (RAP 2011). Relatively low watershed elevations (especially in the extensive Nushagak–Bristol Bay Lowland physiographic division) and the absence of artificial barriers to migration (e.g., dams and roads) mean that not only are streams, lakes, and other aquatic habitats abundant in the Bristol Bay region, but they also tend to be accessible to anadromous salmonids. With very few exceptions, all major lakes in the watershed are accessible to anadromous salmon (Appendix A). Lakes and ponds also play a key role in groundwater dynamics and flow stability (Section 3.3).

Overall physical habitat complexity in the Bristol Bay watershed is higher than in many other systems supporting sockeye salmon populations. Of 1,509 North Pacific Rim watersheds, the Kvichak, Wood, and Nushagak (exclusive of Wood) Rivers ranked third, fourth, and forty-fourth, respectively, in physical habitat complexity, based on an index that included variables such as lake coverage, stream junction density, floodplain elevation and density, and human footprint (Luck et al. 2010, RAP 2011).

3.4.1 Stream Reach Characterization: Attributes

To characterize the stream and river habitats in the Nushagak and Kvichak River watersheds, we described stream and river valley attributes for each of the 52,277 stream and river reaches (54,427 km) in the Nushagak and Kvichak River watersheds documented in the National Hydrography Dataset (NHD) (USGS 2012). We excluded another 27,186 reaches (7,936 km) for which we could not identify reach-specific drainage areas from the analysis. For each reach, we estimated the mean annual streamflow (m^3/s), mean channel gradient (%), and percent of flatland in the contributing watershed lowland (% flat); each attribute is described in detail in the following sections. These attributes were selected because they represent fundamental aspects of the physical and geomorphic settings in streams, providing context for stream and river habitat development and subsequent fish habitat suitability (Burnett et al. 2007). It also was feasible to obtain these attributes for the entire area given available data. These attributes have been used to model habitat suitability for salmon at large scales, for example via intrinsic potential modeling (Burnett et al. 2007, Shallin Busch et al. 2011). We did not develop intrinsic potential models for salmon species in this assessment, as that effort would require multiple years of field data collection for model validation and testing and those data are not currently available. However, our characterization results do provide insights into the distribution of broad-scale habitat conditions within the watersheds, and could provide the basis for future intrinsic potential model development.

3.4.1.1 Channel Gradient

Channel gradient broadly characterizes channel steepness and geomorphic form. Channel gradient and associated aspects of channel morphology influence channel capacity to transport sediment, affecting channel response to disturbance (Montgomery and Buffington 1997). Channel morphology can strongly influence suitability for salmon rearing and spawning. Specific substrate and hydraulic requirements vary slightly by species (Appendix A), but stream-spawning salmon generally require relatively clean gravel-sized substrates with interstitial flow, and sufficient bed stability to allow eggs to incubate in place for months prior to fry emergence (Quinn 2005).

Montgomery and Buffington (1997) proposed a process-based classification of mountain streams. Field data from their study indicated that gradients estimated by digital elevation models (DEMs) provide a useful predictor of channel morphology. We estimated the channel gradient of each stream reach in the Nushagak and Kvichak River watersheds by assessing the gradient of correlated flowpaths across a 30-m-cell National Elevation Dataset DEM (Gesch et al. 2002, Gesch 2007, USGS 2013) (Box 3-1). We adapted the classification scheme put forth by Montgomery and Buffington (1997) to define four gradient classes and predicted channel morphologies for stream reaches at different watershed scales.

- Less than 1%, dune-ripple or pool-riffle morphology.
- At least 1% and less than 3%, plane-bed morphology.
- At least 3% and less than 8%, step-pool morphology.
- At least 8%, cascade morphology.

The substrate and hydraulic conditions required by stream-spawning salmon are most frequently met in stream channels with gradients less than 3% (Montgomery et al. 1999). At the lowest gradients, the channel's capacity to transport fine sediments will be low and substrates may be dominated by sands and other fines, providing suboptimal salmon spawning habitat. A notable exception to this generality occurs in low-gradient, off-channel habitats and ponds that may be dominated by fine sediments but that contain areas of upwelling. These areas are used by riverine-spawning (Eiler et al. 1992) and pond-spawning (Quinn et al. 2012) sockeye salmon. At gradients above 3%, channels develop step-pool or cascade morphologies and the size, stability, and frequency of pockets of suitable spawning substrates decrease substantially (Montgomery and Buffington 1997). In the Bristol Bay region, gradients of productive stream reaches for salmon are typically less than 3%, with gradients less than 1% characterizing the most productive reaches; these habitats include lake outlets and lower tributary reaches, and most of the major spawning reaches and tributaries of the Nushagak and Kvichak River watersheds (Figures 3-11 and 3-12) (Demory et al. 1964). We note, however, that low-gradient watersheds in the coastal plain region of the Nushagak–Bristol Bay Lowland that lack upland headwaters are generally not productive salmon habitats. These streams tend to have lower dissolved oxygen levels, be characterized by fine-textured substrates with high proportions of organic material, and may lack substrates coarser than sand, presumably due to lack of higher-gradient source areas for gravel recruitment (ADF&G 2012, Wiedmer pers. comm.).

Environmental conditions determining suitability for juvenile salmon and adult resident salmonids (e.g., resident Dolly Varden; Box 2-3) are also influenced by gradient. Fish movement can be restricted by the high water velocities and frequent drops found in streams with gradients exceeding 12%, although Dolly Varden have been found at gradients exceeding 15% in southeast Alaska streams

(Wissmar et al. 2010). Gradient and channel roughness also influence the distribution of water velocities and hydraulic conditions in streams, influencing food delivery rates and availability and subsequent energetic demands of drift feeding fish (Hughes and Dill 1990).

BOX 3-1. METHODS FOR CHARACTERIZING CHANNEL GRADIENT

The valley gradient of each stream reach in the Nushagak and Kvichak River watersheds was estimated by assessing the gradient of correlated flowpaths along across a 30-m cell National Elevation Dataset digital elevation model (DEM) (Gesch et al. 2002, Gesch 2007, USGS 2013). We found the measured gradient of the National Hydrography Dataset (NHD) flowlines (based on the elevation of the underlying DEM) was not an accurate representation of channel gradient because of inconsistencies between the mapped streams and rivers in the NHD and the topography described by the DEM. Channel traces in the NHD did not reliably follow the valley floor, and upslope traces and misalignment with the DEM resulted in inaccurate measures of stream gradients and sampled elevations.

We determined that the gradient of streams in a drainage network described by a flow analysis across the DEM would more accurately represent channel morphology given the data available. The drainage network of the DEM paralleled the network of NHD flowlines, but included or excluded some small tributaries and lacked the sinuosity mapped in the NHD.

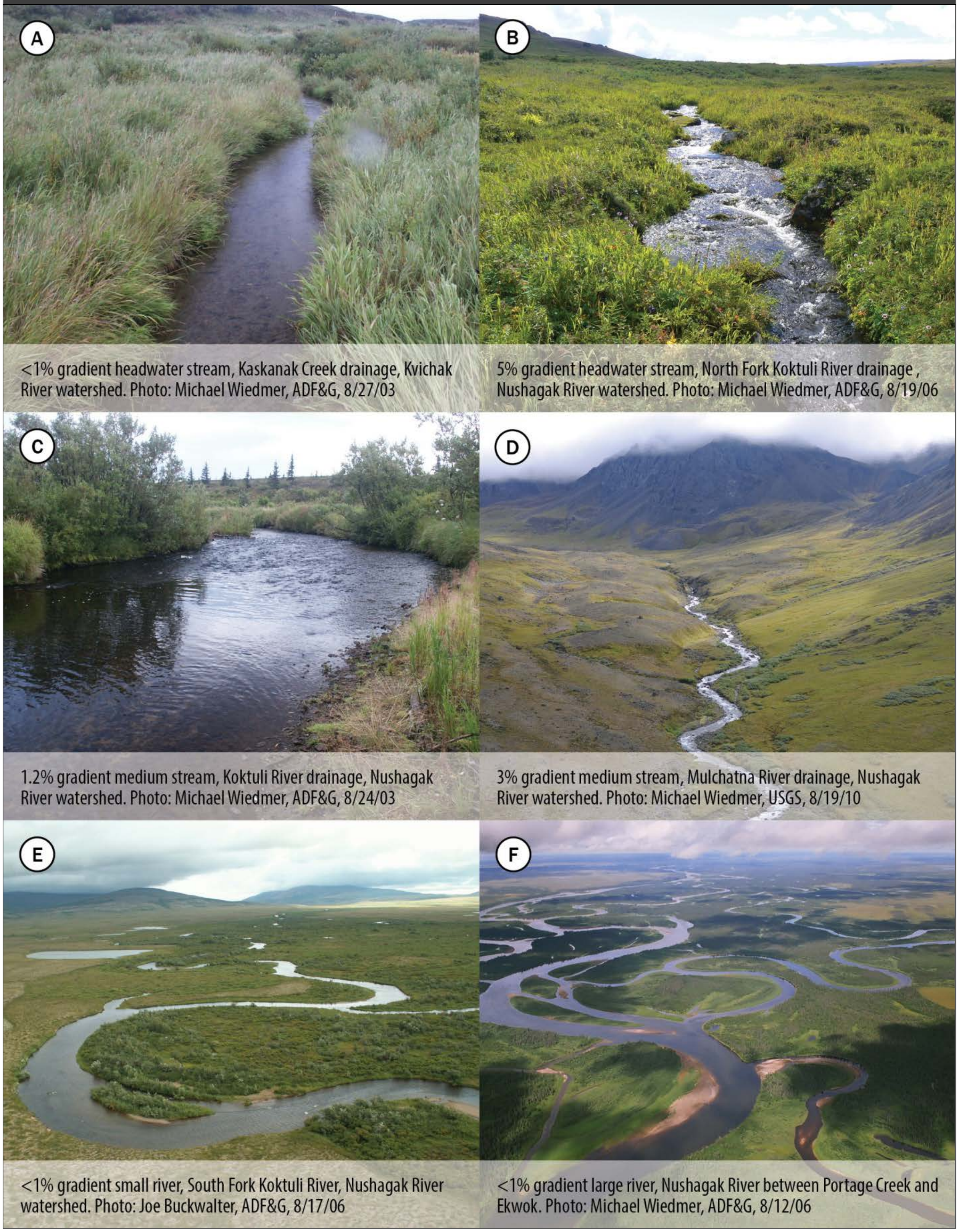
Gradients of flowlines across the DEM were determined using the hydrology tools of the Spatial Analyst extension of ArcGIS. First, the hydraulic network was generated based on the topography of the NHD DEM. Generation of the hydraulic network involved the following tools:

- **Fill.** Sinks in the DEM were filled so that continuous flowpaths could be described.
- **Flow direction.** The steepest path or flow direction was determined from each cell in the DEM.
- **Flow accumulation.** Based on the direction of flow, the total number of cells, or receiving area for each cell in the DEM, was determined.
- **Reclassify.** A threshold value of 0.25 km^2 was applied to the total receiving area output from the previous step to distinguish streams from non-streams.
- **Stream link.** The resulting network was processed to assign unique identifiers to each link in the drainage network.

To determine the gradient of each stream link in the drainage network, and to generate geometry that could assign these values to the reaches of the NHD flowlines, the following tools were used:

- **Extract by mask.** Elevation values underlying the drainage network were isolated from the DEM so that cross-valley slopes would not be measured when determining gradient.
- **Slope.** Gradient along the drainage network was measured between each cell of the isolated drainage network DEM. The drainage DEM confined the slope measures to the flowpath of the drainage network, providing an estimate of stream gradient at each 30-m cell.
- **Watershed.** The output of the Stream Link tool (see above) and the results of the flow direction analysis were used to delineate the drainage basin for each stream link. This geometry was then used to transfer gradient values to the NHD stream reaches.
- **Zonal statistics.** In the drainage basin for each stream segment, the average gradient was determined for all cells with values (i.e., a mean gradient of the stream segment). Mean gradient values were then assigned to the drainage basin geometry.
- **Zonal statistics as table.** The mean gradient for each drainage basin was used to calculate the channel gradient for each NHD flowline. This tool measured the length-weighted mean of the gradients for each reach (as defined by the NHD Reach Code attribute) from the means calculated for each drainage basin. Typically, the NHD flowlines occupied no more than two drainage basins. The resulting gradient estimates were appended to the table of NHD flowlines.

Figure 3-11. Examples of different stream size and gradient classes in the Nushagak and Kvichak River watersheds.



(A) <1% gradient headwater stream, Kaskanak Creek drainage, Kvichak River watershed. Photo: Michael Wiedmer, ADF&G, 8/27/03

(B) 5% gradient headwater stream, North Fork Koktuli River drainage , Nushagak River watershed. Photo: Michael Wiedmer, ADF&G, 8/19/06

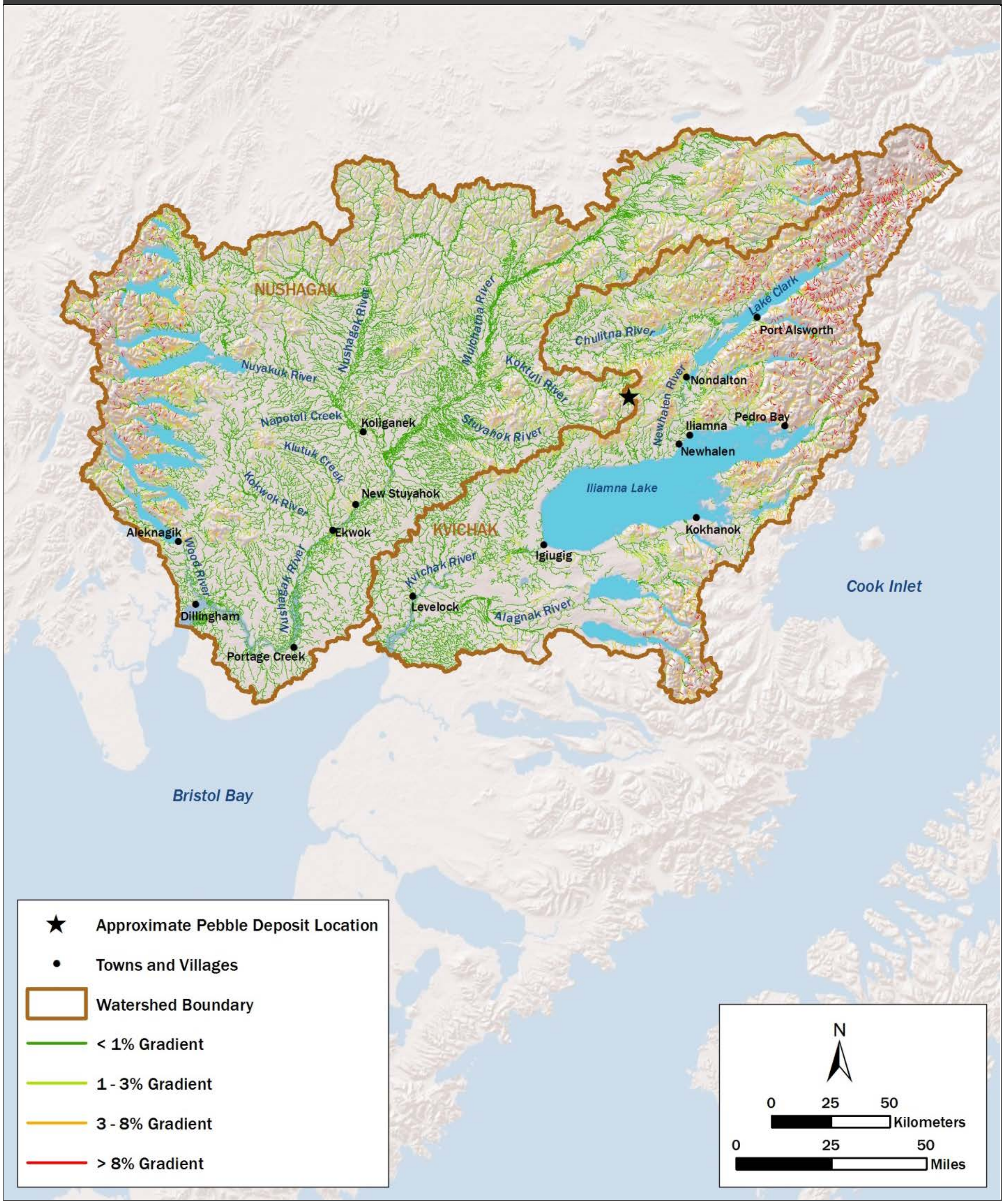
(C) 1.2% gradient medium stream, Koktuli River drainage, Nushagak River watershed. Photo: Michael Wiedmer, ADF&G, 8/24/03

(D) 3% gradient medium stream, Mulchatna River drainage, Nushagak River watershed. Photo: Michael Wiedmer, USGS, 8/19/10

(E) <1% gradient small river, South Fork Koktuli River, Nushagak River watershed. Photo: Joe Buckwalter, ADF&G, 8/17/06

(F) <1% gradient large river, Nushagak River between Portage Creek and Ekwok. Photo: Michael Wiedmer, ADF&G, 8/12/06

Figure 3-12. Channel gradient classes in the Nushagak and Kvichak River watersheds. Valley gradient was assessed by measuring drainage channel slope across the watersheds' landscapes (Box 3-1).



3.4.1.2 Mean Annual Streamflow

Mean annual streamflow is a metric of stream size, an important determinant of available habitat space (capacity) for stream fishes. The relationship between mean annual streamflow and habitat capacity for rearing juvenile salmon can vary with streamflow regime and other limiting factors, but is generally positive when other factors are not constraining.

Mean annual streamflow for each stream reach within the Nushagak and Kvichak River watersheds was estimated using regression equations for the prediction of mean annual streamflow, based on drainage area and historical mean annual precipitation in southwestern Alaska (Parks and Madison 1985) (Box 3-2). We defined four classes of stream size based on these mean annual streamflow calculations.

- Small headwater streams (less than 0.15 m^3/s), including many of the tributaries of the South and North Fork Koktuli Rivers and Upper Talarik Creek.
- Medium streams (0.15 to 2.8 m^3/s), including the upper reaches and larger tributaries of the South and North Fork Koktuli Rivers and Upper Talarik Creek.
- Small rivers (2.8 to 28 m^3/s), including the middle to lower portions of South and North Fork Koktuli Rivers, and Upper Talarik Creek, and the mainstem Koktuli River.
- Large rivers (greater than 28 m^3/s), including the Mulchatna River below the confluence with the Koktuli River, the Newhalen River, and other larger rivers.

All five species of Pacific salmon present in the Bristol Bay region use portions of large and small rivers and medium streams for migration, spawning, and/or rearing habitat. Research in the Wood River system suggests that larger stream sizes allow multiple salmon species to coexist, perhaps due to habitat partitioning made possible by increased space and habitat diversity (Pess et al. 2013). Salmon also use small streams in the Bristol Bay region for spawning and rearing, but use of these habitats may be constrained by shallow depths, insufficient streamflow to allow passage, the unavailability of open water in winter, or other limitations related to stream size.

Salmonid species differ in their propensities for small streams. Dolly Varden have been documented using all stream sizes, including some of the smallest channels. Of the Pacific salmon species, coho salmon are most likely to use small streams for spawning and rearing, and have been observed in many of the smaller streams near the Pebble and other deposits. Larger-bodied Chinook salmon adults are less likely to access smaller streams for spawning (Quinn 2005). However, juvenile Chinook salmon are observed in small tributaries where spawning has not been documented.

BOX 3-2. METHODS FOR CHARACTERIZING MEAN ANNUAL STREAMFLOW

Mean annual streamflow for each stream reach in the Nushagak and Kvichak River watersheds was estimated using regression equations, based on drainage area and historical mean annual precipitation data in southwestern Alaska (Parks and Madison 1985). Total drainage area was determined for reaches along the National Hydrography Dataset (NHD) flowlines by developing a drainage-corrected digital elevation model (DEM) based on the National Elevation Dataset (NED). Although the underlying topography and catchments described by the NED remained the same, the elevations underlying the NHD flowlines and in their immediate vicinity were lowered and smoothed such that runoff conformed to the geometry of the NHD flowlines.

Using the drainage-corrected DEM, we estimated total catchment area above any location in the drainage network. The NED DEM was corrected to better conform to the NHD flowlines and drainage areas were calculated using the following tools of the ArcHydro and Spatial Analyst tools of the ArcGIS suite:

- **DEM reconditioning.** The elevations of the DEM were altered along the NHD flowlines and in their immediate vicinity. Parameters used for this tool were a 10-m reduction of elevations along the flowline, a 5-cell (150-m)-wide transition zone on either side of the flowline, and a post-process 1-km reduction in elevations along the flowlines. The initial elevation reduction and transition width were found to adequately capture flows and maintain those flows within the channel geometry. The post-processing adjustment is a more arbitrary value intended to confine flows to the channels once captured.
- **Fill.** Sinks in the reconditioned DEM were filled so that continuous flowpaths could be described.
- **Flow direction.** The steepest path or flow direction was determined from each cell in the DEM.
- **Flow accumulation (drainage area).** Based on the direction of flow, the total number of cells, or receiving area for each cell in the DEM, was determined. These values were multiplied by 0.0009 to convert the area of each cell (900 m^2) to square kilometers.
- **Flow accumulation (accumulated precipitation).** Due to variation in precipitation patterns across the study area, the average accumulated precipitation was calculated by using the flow accumulation tool with a weight assigned to each cell based on the average annual precipitation data for 1971 to 2001 (SNAP 2012). The result was divided by the total number of cells accumulated at each location on the grid to determine the average accumulated annual precipitation.

The output drainage area raster and raster coverage of average annual precipitation were used as inputs for the mean annual streamflow regression equation developed by Parks and Madison (1985) for southwestern Alaska:

$$Q = (10^{-1.38})*(DA^{0.98})*(P^{1.13})$$

where Q is mean annual flow in cubic feet per second, DA is drainage basin area in square miles, and P is mean annual precipitation in inches per year. We used the median mean annual streamflow value from the cells within the drainage network that corresponded to each NHD flowline as the estimate of mean annual streamflow for the stream segment.

3.4.1.3 Proportion of Flatland in Lowland

Stream channels in mountainous and foothill terrain are laterally constrained by their valley walls to varying degrees. Degree of channel constraint influences channel form, including the development of off-channel habitats, variability in local channel gradients, and hydraulic conditions during over-bank flows. Unconstrained channels generally have higher complexity of channel habitat types and hydraulic conditions and higher frequencies of off-channel habitats such as side channels, sloughs, and beaver ponds. Such habitat complexity can be beneficial to salmon by providing a diversity of spawning and rearing habitats throughout the year (Stanford et al. 2005).

To provide an index of the degree of channel constraint expected within each stream reach, we estimated the percent of flatland (less than 1% slope) within lowland (area below median elevation) for each stream reach's adjacent drainage basin (Box 3-3). Visual inspection of portions of the study area where high-resolution aerial photographs were available showed that channels were typically unconstrained when the proportion of flatland in lowland exceeded 5%. This threshold was used to identify two classes:

- Less than 5% flatland in lowland, indicating reaches are constrained and have limited floodplain area. These reaches are classified as having low or no floodplain potential.
- Greater than or equal to 5% flatland in lowland, indicating reaches are unconstrained and have high likelihood for floodplain development. These reaches are classified as having floodplain potential.

In the Bristol Bay region, streams that are unconstrained and able to develop complex off-channel habitats are more likely to provide a diversity of channel habitat types and hydraulic conditions, creating favorable conditions, particularly for salmonid rearing. For Chinook and coho salmon, as well as river-rearing sockeye salmon that may overwinter in streams, such habitats may be particularly valuable. The percent flatland in lowland metric is not a perfect index of channel constraint, however. Channels in flat lowlands such as the coastal Nushagak–Bristol Bay Lowlands physiographic division (Figure 3-1) may actually be incised into fine-grained sediments with very little off-channel habitat complexity. In the glacially worked landscapes of the Bristol Bay region, streams may be constrained by relatively flat valley terraces and moraine deposits that are not distinguishable on the coarse-scale DEM available for the region. Terraces are a common feature in portions of the region, but the degree to which terrace constraint influences these results could not be determined from the existing DEM. In steep, mountainous terrain, narrow valleys may occasionally allow for unconstrained stream channel development across low-gradient floodplains, but these features are likely not always detected with the DEM resolution currently employed for this effort.

3.4.2 Stream Reach Characterization: Results

We estimated the three stream-reach attributes discussed above in four geographically defined areas that vary in scale and location (as described in Section 2.2.2).

- The Nushagak and Kvichak River watersheds (Scale 2).
- The mine scenario watersheds—that is, the South Fork Koktuli River, the North Fork Koktuli River, and the Upper Talarik Creek watersheds (Scale 3).
- The streams lost to the Pebble 6.5 scenario footprint (Scale 4).
- The subwatersheds of the transportation corridor area (Scale 5).

In this section, we summarize results for the Nushagak and Kvichak River watersheds to broadly characterize the region. Results for the other three geographic scales are reported later in the assessment (Sections 7.2.1 and 10.2), where we evaluate potential impacts of large-scale mining.

BOX 3-3. METHODS FOR CHARACTERIZING PERCENT FLATLAND IN LOWLAND

The relative degree of channel constraint in the Nushagak and Kvichak River watersheds was estimated by calculating the percent of flatland (<1% slope) within lowland (area below median elevation) in each stream reach's adjacent drainage basin. These calculations included the delineation of drainage basins of the drainage-corrected drainage network (developed for the mean annual streamflow analysis; see Box 3-2) as well as elevation and slope analyses of the unaltered digital elevation model (DEM).

To establish the drainage basin geometry of the drainage-corrected flow analysis, the following Spatial Analyst tools were applied within an ArcGIS workspace.

- **Reclassify.** A threshold value of 0.25 km^2 was applied to the total receiving area output from the drainage-corrected flow analysis to distinguish streams from non-streams.
- **Stream link.** The resulting network was processed to assign unique identifiers to each link in the drainage network.
- **Watershed.** The output of the Stream Link tool (see above) and the results of the flow direction analysis were used to delineate the drainage basin for each stream link. This geometry was used as the geographic extent of analysis for each stream segment.

Areas of flatland and lowland were then identified for each drainage basin. The unaltered National Elevation Dataset DEM was processed with the following Spatial Analyst tools from ArcGIS.

- **Slope.** The original (not drainage-corrected) DEM was analyzed to determine slope (%) across the extent of the Nushagak and Kvichak River watersheds.
- **Reclassify.** A threshold value of 1% was applied to the slope analysis, and attributes were assigned across the study area as meeting or not meeting the flatland criteria.
- **Zonal statistics.** In the drainage basin for each stream segment, the minimum and maximum elevations were determined using the Zonal Statistics tool. These values were used to identify the median elevation for each watershed.
- **Reclassify.** The DEM was classified as meeting or not meeting the lowland criteria based on results of the previous step.

Finally, the percent flatland in lowland for each stream reach's drainage basin was calculated using the following steps.

- **Times.** Areas of flatland outside of lowland areas were eliminated by multiplying the flatland and lowland rasters. The flatland and lowland rasters used 1 and 0 values for true and false, respectively, so both conditions were required to return a positive result for flatland in lowland.
- **Zonal statistics.** The total areas of lowland and flatland within lowland were calculated for each drainage basin.
- **Divide.** The percent flatland in lowland was determined for each drainage basin by dividing the area of flatland in lowland by the area of lowland in each drainage basin.
- **Zonal statistics as table.** The average value of percent flatland in lowland for each stream reach was calculated and added to a table, which was then appended to the National Hydrography Dataset (NHD) flowline data table. Although the mean statistic was used to ascertain these values for the NHD flowlines, the flowlines typically had a one-to-one correlation with drainage basins, as the basins were based on the drainage-corrected flow analysis.

We characterized 54,427 km of streams and 52,277 stream and river reaches in the Nushagak and Kvichak River watersheds. Reach attributes reflected the hydrologic landscapes in which the reaches occurred and upstream within each reach's drainage (Section 3.2). Relatively low-gradient stream channels extend far up into the headwaters of the upper Mulchatna and Nushagak River watersheds (Figure 3-12), allowing salmon to access headwater streams. High-gradient conditions are primarily found in the headwaters of Lake Clark and Iliamna Lake tributaries and the headwaters of the Alagnak, Wood, Kokwok, and Nuyakuk Rivers (Figure 3-12). Valley flatland is heavily concentrated in the Nushagak–Bristol Bay Lowlands physiographic division and along the larger rivers, but includes significant wider-valley reaches in the Nushagak–Big River Hills, Southern Alaska Range, and Aleutian Range divisions (Figure 3-13).

The majority of stream channel length (75%) in the Nushagak and Kvichak River watersheds is composed of low-gradient (less than 3%), medium and small (less than 2.8 m^3/s mean annual streamflow) streams (Table 3-3, Figures 3-12 and 3-14). The extent of flatland in valley lowlands is strongly associated with gradient. For streams with less than 1% gradient, 55% have high floodplain potential (i.e., greater than or equal to 5% flatland in lowland). In contrast, less than 5% of streams with gradients greater than 1% have high floodplain potential. Stream reaches with greater than 3% gradient were only found in landscapes where floodplain potential was low (i.e., less than or equal to 5% flatland in lowland). Overall, these results reveal the high proportion of stream channels in these watersheds that possess the broad geomorphic and hydrologic characteristics enabling the development of stream and river habitats highly suitable for fishes such as Pacific salmon, Dolly Varden, and rainbow trout.

3.5 Water Quality

3.5.1 Water Chemistry

Water quality of streams near the Pebble deposit has been characterized extensively (PLP 2011, Zamzow 2011). The streams draining the watersheds in the Pebble deposit area (Figure 2-5) are neutral to slightly acidic, with low conductivity, hardness, dissolved solids, suspended solids, and dissolved organic carbon (see Section 8.2.1.1 for more detailed discussion of water chemistry in streams draining the mine scenario watersheds). In those respects, they are characteristic of undisturbed streams. However, as would be expected for a metalliferous site, levels of sulfate and some metals (copper, molybdenum, nickel, and zinc) are elevated, particularly in the South Fork Koktuli River. PLP (2011) found that copper levels in some samples from the South Fork Koktuli River exceeded Alaska's chronic water quality standard. However, most of the exceedances were in or close to the deposit and the number and magnitude of exceedances decreased with distance downstream (PLP 2011: Figure 9.1-35, 60, 61, 65, and 66).

Figure 3-13. Likelihood of floodplain potential, as measured by the percent flatland in lowland areas, for the Nushagak and Kvichak River watersheds. Flatland refers to land with less than 1% slope; lowland areas are defined as areas below the midpoint elevation within the drainage basin of each stream reach (Box 3-3).

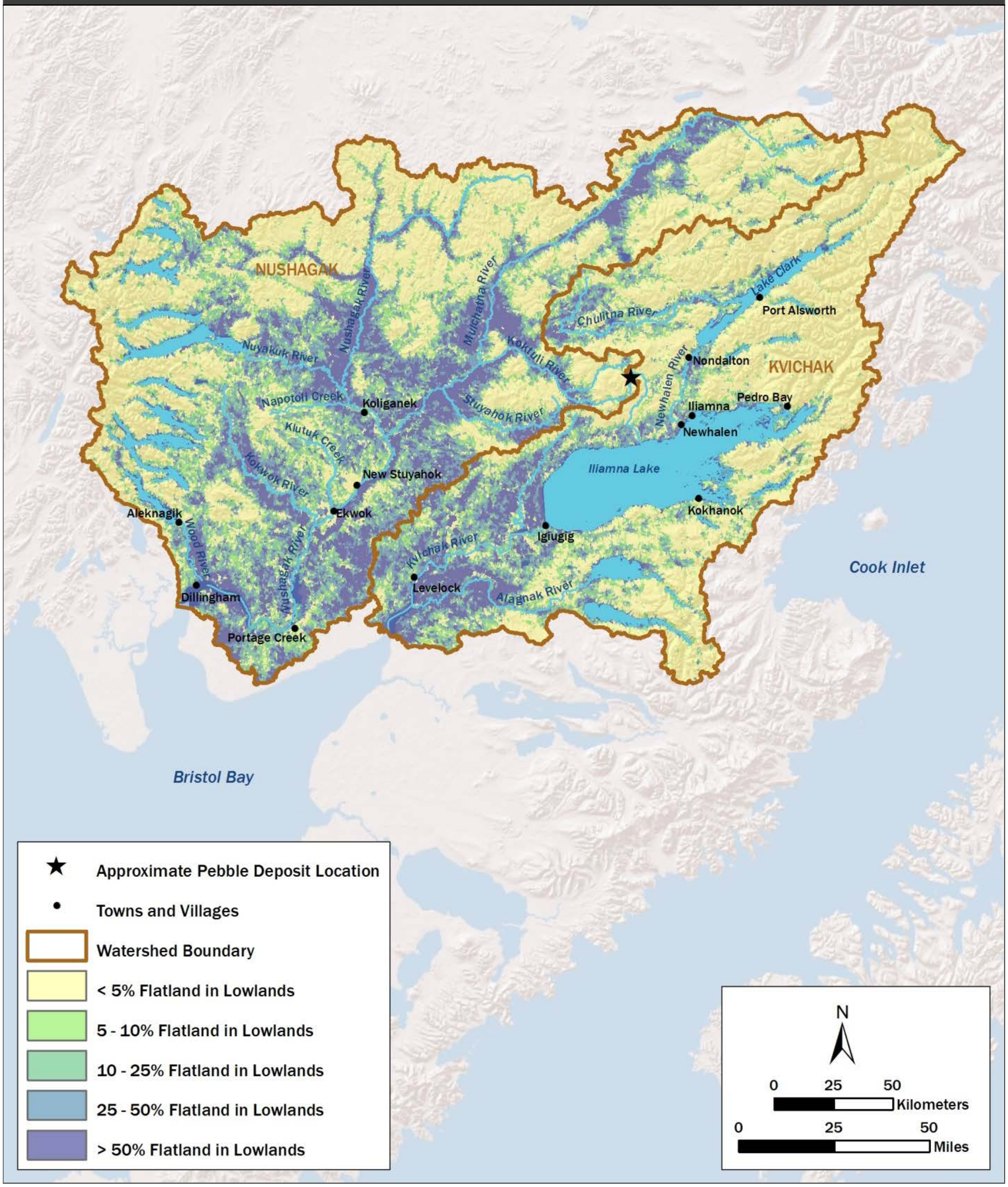


Figure 3-14. Stream size classes in the Nushagak and Kvichak River watersheds as determined by mean annual streamflow. Mean annual streamflow for streams and rivers was estimated using drainage area and mean annual precipitation (Box 3-2).

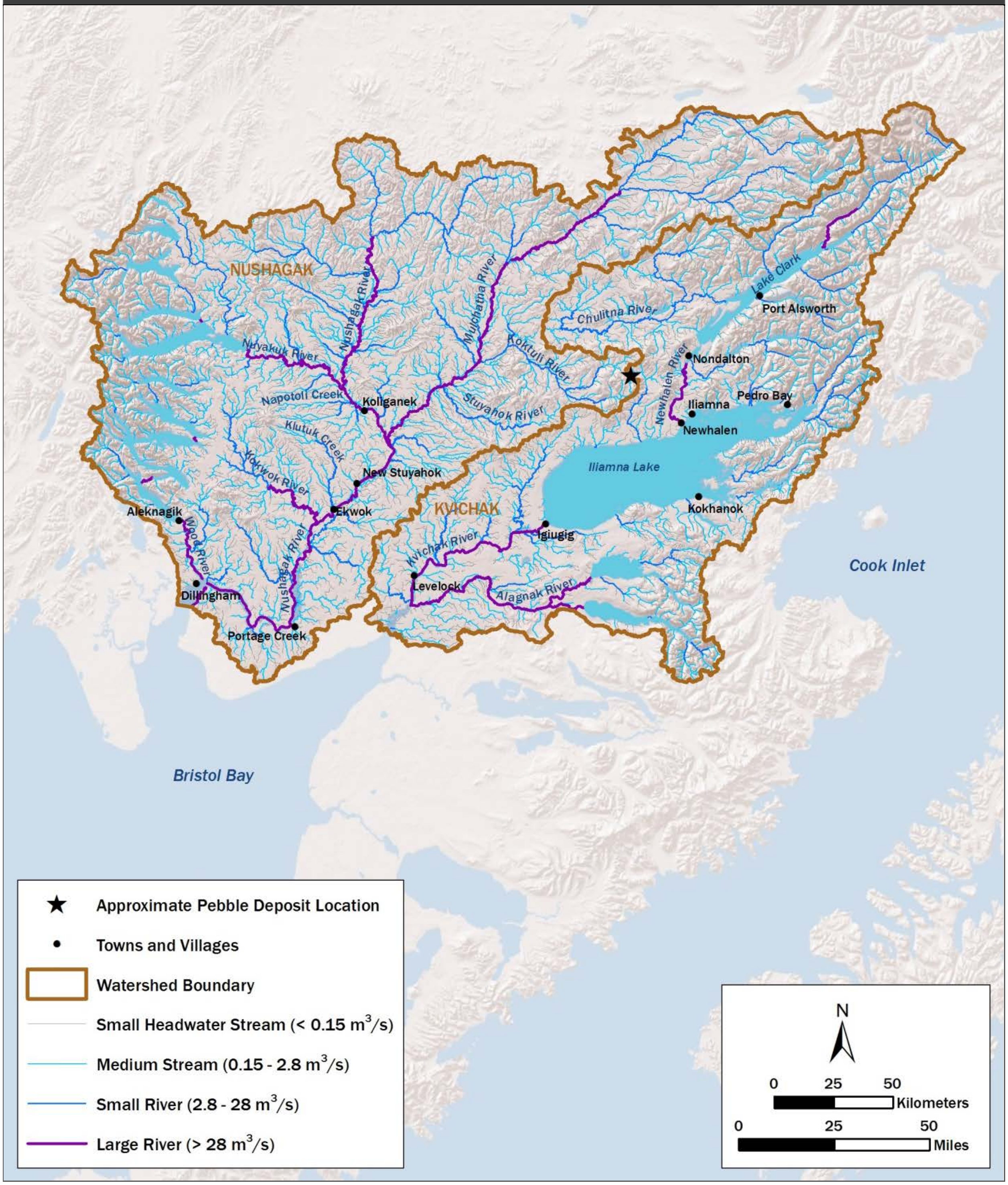


Table 3-3. Proportion of stream channel length within the Nushagak and Kvichak River watersheds classified according to stream size (based on mean annual streamflow in m³/s), channel gradient (%), and floodplain potential (based on % flatland in lowland). Gray shading indicates proportions greater than 5%; bold indicates proportions greater than 10%.

Stream Size	Gradient							
	<1%		≥1% and <3%		≥3% and <8%		≥8%	
	FP	NFP	FP	NFP	FP	NFP	FP	NFP
Small headwater streams[a]	**27%**	5%	3%	**13%**	0%	8%	0%	3%
Medium streams[b]	**20%**	3%	1%	3%	0%	2%	0%	1%
Small rivers[c]	6%	1%	0%	0%	0%	0%	0%	0%
Large rivers[d]	2%	0%	0%	0%	0%	0%	0%	0%

Notes:
[a] 0–0.15 m³/s; most tributaries in the mine footprints.
[b] 0.15–2.8 m³/s; upper reaches and larger tributaries of the South Fork Koktuli, North Fork Koktuli, and Upper Talarik Creek.
[c] 2.8–28 m³/s; mid to lower portions of the South Fork Koktuli, North Fork Koktuli, and Upper Talarik Creek, including the mainstem Koktuli River.
[d] >28 m³/s; the Mulchatna River below the Koktuli confluence, the Newhalen River, and other large rivers.
FP = high floodplain potential (≥5% flatland in lowland); NFP = no or low floodplain potential (<5% flatland in lowland).

3.5.2 Water Temperature

Water temperature data (PLP 2011: Appendix 15.1E, Attachment 1) indicate significant spatial variability in thermal regimes. Average monthly stream water temperatures in the Pebble deposit area in July or August can range from 6°C to 16°C. Longitudinal profiles of temperature indicate that stream temperatures in the Pebble deposit area do not uniformly increase with decreasing elevation (PLP 2011). This is often due to substantial inputs of cooler water from tributaries or groundwater (PLP 2011). Extensive glacially reworked deposits with high hydraulic conductivity allow for extensive connectivity between groundwater and surface waters in the region (Power et al. 1999). This groundwater–surface water connectivity has a strong influence on the hydrologic and thermal regimes of streams in the Nushagak and Kvichak River watersheds, and provides a moderating influence against both summer heat and winter cold extremes in stream reaches where this influence is sufficiently strong. The range of spatial variability in temperatures in the Pebble deposit area (PLP 2011) is consistent with streams influenced by a variety of thermal modifiers, including upstream lakes, groundwater, or tributary contributions (Mellina et al. 2002, Armstrong et al. 2010).

3.6 Seismicity

The Alaska Earthquake Information Center and U.S. Geological Survey (USGS) collect data on earthquakes occurring in Alaska at seismological monitoring stations throughout the state. Earthquakes in Alaska range from minor events detected only by sensitive instruments, to the largest earthquake ever recorded in North America (the 1964 Good Friday earthquake near Anchorage, magnitude 9.2) (Table 3-4, Figure 3-15).

Table 3-4. Examples of earthquakes in Alaska.

Date	Depth (km)	Magnitude[a]	Distance and Direction from the Pebble Deposit
March 28, 1964	25	9.2	469 km east-northeast
November 3, 2002	4.2	7.2	593 km northeast
September 25, 1985	184	4.9	61 km southeast
July 13, 2007	6.2	4.3	30 km west-southwest
March 25, 2012	12	3.0	122 km east

Notes:

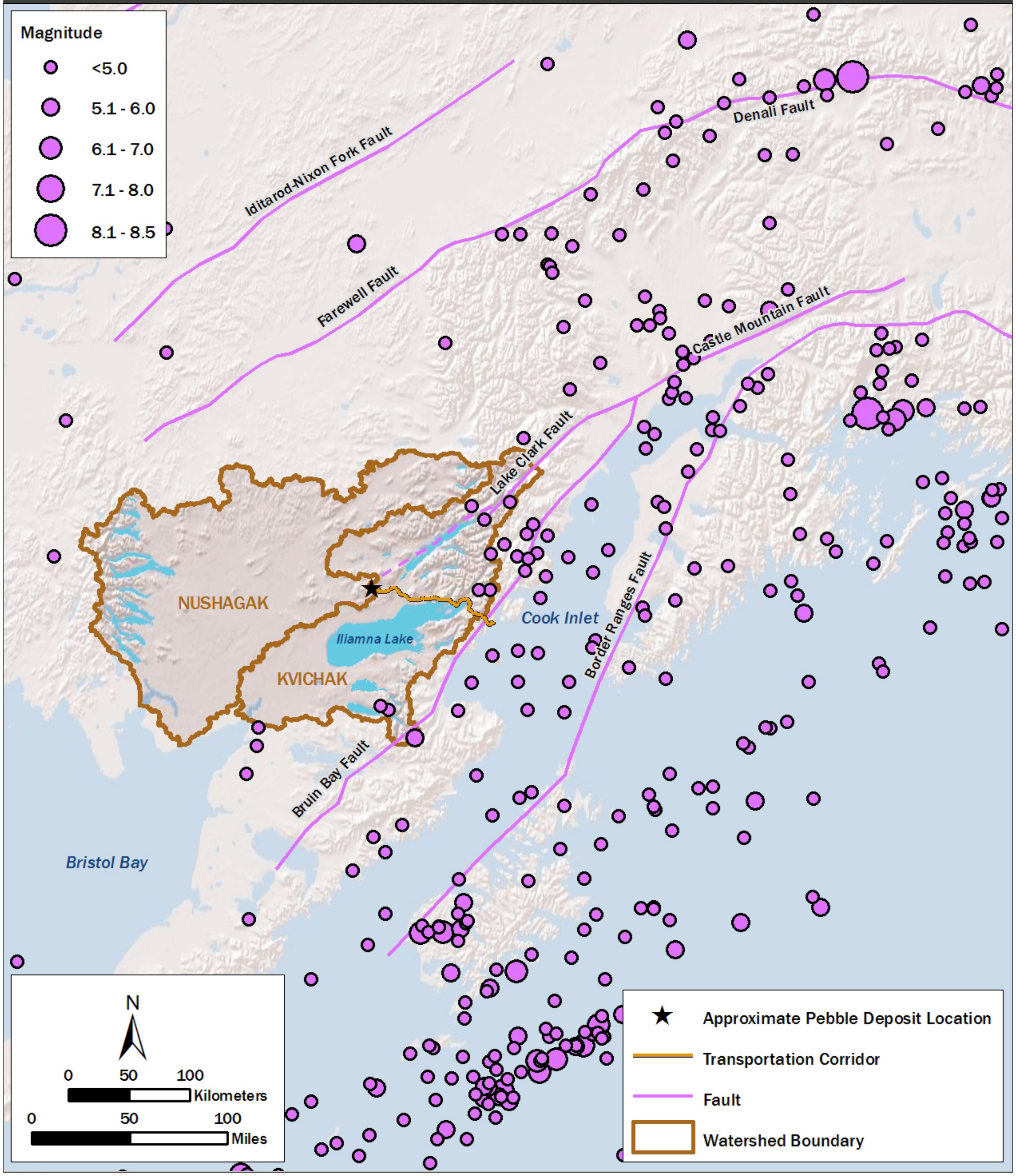
[a] Local magnitude as reported by the Alaska Earthquake Information Center. Note that earthquakes in the range of magnitudes 1.5 to 3.6 occur regularly in the Lake Clark area (data not shown). These earthquakes are centered at a depth of 100 km or greater.

Southwestern Alaska experiences a large number of earthquakes related to the presence of four active moving blocks of crust associated with large fault systems. These faults are, from north to south, the Tintina-Kaltag Fault, the Iditarod-Nixon Fork Fault, the Denali-Farewell Fault, the Lake Clark–Castle Mountain Fault system, the Bruin Bay Fault, and the Border Ranges Fault (Figure 3-15). Some sections along these faults are seismically active and have generated earthquakes in the past. The size of an earthquake is directly related to the area of the fault that ruptures; thus, longer faults are capable of producing larger earthquakes. The damage caused by an earthquake is related to the size of and distance from the earthquake. The effects of an earthquake diminish with distance, so more damage occurs at the epicenter than at a point several kilometers away.

The Lake Clark–Castle Mountain Fault system, with a mapped length of 225 km, is the fault located nearest to the Pebble deposit. The northeast-southwest trending Lake Clark Fault is the western extension of the Castle Mountain Fault (Koehler and Reger 2011). The western terminus of the Lake Clark Fault has not been identified, but was originally interpreted to be near the western edge of Lake Clark. Recent studies by USGS reinterpreted the position of the Lake Clark Fault further to the northwest, potentially bringing it as close as 16 km to the Pebble deposit (Haeussler and Saltus 2004). Haeussler and Saltus (2004) acknowledge that the fault could extend closer than 16 km, but data are not available to support this interpretation.

There are few residents and no long-term seismic monitoring station records in the area of the Pebble deposit, which make it difficult to assess accurately the recent seismic history of the area. As a result, the paleoseismic history of the western part of the Lake Clark Fault is unknown (Koehler and Reger 2011). USGS has concluded that there is no evidence for fault activity or seismic hazard associated with the Lake Clark Fault in the past 1.8 million years, and no evidence of movement along the fault northeast of the Pebble deposit since the last glaciations 11,000 to 12,000 years ago (Haeussler and Waythomas 2011).

Figure 3-15. Seismic activity in southwestern Alaska. Location and magnitude of significant, historic earthquakes (USGS 2010) that caused deaths, property damage, and geological effects or were otherwise experienced are shown. Fault lines are based on Haeussler and Saltus (2004), including the preferred drawing of the Lake Clark Fault (dashed purple line).



The 1980 USGS map of the structural geology of the Iliamna Lake quadrangle shows several mapped faults in the Tertiary-age volcanic rocks that host the area's mineral deposits. Geologic mapping conducted by consulting firms for PLP identified numerous faults in the Pebble deposit area. The mapped faults shown in both these sources are all considerably shorter than the Lake Clark Fault, and therefore by themselves have a very limited capability to produce damaging earthquakes. The largest mapped fault in the Pebble deposit area is an unnamed northwest-trending fault approximately 13 km southwest of the deposit, approximately 16 km in length. There are several short (less than 4 km) faults mapped within and near the mine scenario watersheds (the Z-series faults), about half of which have northeast-southwest orientations. The faults show vertical displacement ranging from tens of meters to over 900 m, and are interpreted to have formed coincident with mineralization (Ghaffari et al. 2011). Although there is no evidence that the Lake Clark Fault extends closer than 16 km to the Pebble depositor that there is a continuous link between the Lake Clark Fault and the northeast-trending faults at the mine site, mapping the extent of subsurface faults over long, remote distances is difficult and has a high level of uncertainty.

Not all earthquakes occur along the mapped sections of faults. In some instances, stresses build up and cause earthquakes in rock outside of known pre-existing faults. Earthquakes can occur on previously unidentified, minor, or otherwise inactive faults, or along deeper faults that are not exposed at the surface. Although these *floating earthquakes* are generally smaller and less frequent than those associated with faults, they may occur at locations closer to critical structures than the nearest mapped capable fault. Small earthquakes can be induced when reservoirs or impoundments are constructed (Kisslinger 1976), altering the soil and rock stresses and increasing pore pressure along pre-existing zones of weakness. Induced earthquakes are generally small, but can occur frequently and cause landslides and structural damage to earthen structures.

Interpreting seismicity in the Bristol Bay area is difficult because of the remoteness of the area, its complex bedrock geology overlain by multiple episodes of glacial activity, and the lack of historical records on seismicity. Thus, there is a high degree of uncertainty in determining the location and extent of faults, their capability to produce earthquakes, whether these or other geologic features have been the source of past earthquakes, and whether they have a realistic potential for producing future earthquakes. Large earthquakes have return periods of hundreds to thousands of years, so there may be no recorded or anecdotal evidence of the largest earthquakes on which to base future predictions.

3.7 Existing Development

Unlike most other areas supporting Pacific salmon populations, the Bristol Bay watershed is undisturbed by significant human development. It is located in one of the last remaining virtually roadless areas in the United States (Section 6.1.3.1). Large-scale, human-caused modification of the landscape—a factor contributing to extinction risk for many native salmonid populations (Nehlsen et al. 1991)—is absent, and development in the watershed consists of only a small number of towns, villages, and roads. The Bristol Bay watershed also encompasses Iliamna Lake, the largest undeveloped lake in the United States.

The primary human manipulation of the Bristol Bay ecosystem is the marine harvest of approximately 70% of salmon returning to spawn. However, commercial salmon harvests are the Alaska Department of Fish and Game's (ADF&G's) second priority for fish management; its first priority is to ensure that sufficient fish migrate into rivers to maintain a sustainable fishery, and thus sustainable salmon-based ecosystems. No hatchery fish are reared or released in the Bristol Bay watershed, whereas approximately 5 billion hatchery-reared juvenile salmon are released annually across the North Pacific (Irvine et al. 2009). Given the potential for hatchery fish to have negative effects on wild fish (e.g., Araki et al. 2009, Rand et al. 2012), this lack of hatchery fish is notable.

3.8 Climate Change

Thus far, this chapter has focused on the current physical environment in the Bristol Bay watershed. In the future, over time scales at which large-scale mining will potentially affect these watersheds, this physical environment is likely to change substantially—particularly in terms of climate and, by extension, hydrology. Over the past 60 years, much of Alaska has been warming at twice the average rate of the United States and many parts of the world (ACIA 2004). Throughout Alaska, changes such as warmer temperatures, melting glaciers, declining sea ice, and declining permafrost have already occurred (Serreze et al. 2000, Stafford et al. 2000, ACIA 2004, Hinzman et al. 2005, Liston and Hiemstra 2011, Markon et al. 2012). However, there is limited evidence over the last decade that suggests air temperature in much of Alaska has cooled, due to changes in the Pacific Decadal Oscillation and weakening of the Aleutian low (Wendler et al. 2012). Climate models suggest that warming throughout Alaska is projected to continue, and it is likely to lead to changes in the type and timing of precipitation, decreased snowpack and earlier spring snowmelt, and subsequent changes in hydrology similar to projections in Arctic regions (Hinzman et al. 2005).

Using methods detailed in Box 3-4, we used the multi-model average A2 emissions scenario developed by SNAP (2012) to generate 30-year means for future temperature and precipitation patterns in the Bristol Bay region. We focused on characterizing possible climate change impacts using the A2 emissions scenario 30-year mean for the end of this century (2071–2100) as an upper bound estimate of climate change effects expected for this region with current modeling. Similar trends in temperature and precipitation, but with smaller magnitudes, are shown for effects earlier in the century or with more benign emission scenarios.

BOX 3-4. METHODS FOR CLIMATE CHANGE PROJECTIONS

To project temperature and precipitation changes over the next century, we used data from the Scenarios Network for Alaska and Arctic Planning (SNAP). A full description of the SNAP data and methodology used is available on the SNAP website (SNAP 2012).

From the SNAP dataset, we used downscaled values of monthly mean temperature and precipitation. The historical dataset is derived from the Climate Research Unit (CRU) at the University of East Anglia for 1901 to 2009 (CRU 2012). The CRU data are downscaled using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) 1971 to 2000 monthly climatologies for Alaska (PRISM Climate Group 2012), which take into account elevation, slope, and aspect. SNAP then developed downscaled monthly projections of temperature and climate for Alaska under three emissions scenarios developed by the Intergovernmental Panel on Climate Change for the Coupled Model Intercomparison Project. SNAP uses five global climate models (GCMs) [cccma_cgcm31, mpi-echam5, gfdl_cm21, ukmo_hadcm3, and miroc3_2_medres] that best characterize the Arctic region up to the year 2100 (Walsh et al. 2008). These emissions scenarios are:

- the B1 scenario, which represents a best-case emissions scenario;
- the A1B scenario, which represents a middle-of-the-road emissions scenario; and
- the A2 scenario, which represents a worst-case emissions scenario.

For this assessment, we use the SNAP 5-model average for the A2 scenario of the best-performing GCMs to consider a worst-case climate change scenario for the Bristol Bay region. Although uncertainty is inherent in climate modeling due to many factors, the SNAP 5-model average tends to perform better than any single model under the A2 scenario. Using the SNAP model, we calculated 30-year normal values, or average values over a 30-year period, for temperature and precipitation over 1971 to 2000 (historical) and over 2011 to 2040, 2041 to 2070, and 2071 to 2100 under the three emissions scenarios. We focused on the A2 scenario for the years 2071 to 2099 (the year 2100 is not included because one of the GCMs used in the average did not include that year). Using the SNAP data, we calculated changes in temperature and precipitation at three scales: the Bristol Bay watershed (Figure 2-3), the Nushagak and Kvichak River watersheds (Figure 2-4), and the mine scenario watersheds (Figure 2-5). We also calculated annual potential evapotranspiration (PET) (Hamon 1961) and annual water surplus (annual precipitation minus PET) for the Bristol Bay watershed and the Nushagak and Kvichak River watersheds.

Data for the appropriate watersheds were extracted from the SNAP dataset, which covers the entire state of Alaska. The resolution of the SNAP dataset is a 771-m grid. Any grid pixel intersecting a watershed boundary was included, even if the intersection was minimal, to account for the full range of possible temperature and precipitation values across the watersheds. In all cases, the values reported in the assessment represent the geographic spatial average across the entire watershed over an average of 30 years. Precipitation and temperature differences between the two periods were calculated as the geographic spatial average across the entire watershed of the raster representing the A2 scenario (2071 to 2099), minus the present period. Precipitation percent differences were calculated as the geographic spatial average across the entire watershed of the raster representing the difference between the A2 scenario (2071 to 2099) and the present period, divided by the present period and multiplied by 100.

Water surpluses under historical and future periods were calculated for each calendar month and summed to arrive at annual values. Differences between periods were calculated by subtracting the present value from the A2 scenario (2071 to 2099) value. It is important to remember that surplus measurements were calculated at the annual level and do not represent monthly or seasonal differences across a single scenario or between multiple scenarios.

Uncertainty is an inherent issue when dealing with projected temperature, precipitation, and water surplus values because of local variability and uncertainty in GCMs. Using average values for the five best-performing GCMs for the Arctic and calculating mean values over 30-year periods helps to reduce uncertainty; however, this averaging also decreases precision in predicting extreme events.

By the end of the century, based on SNAP (2012) data for the A2 emissions scenario, the multi-model average annual air temperature in the Bristol Bay region is projected to increase by approximately 4°C, with an approximately 6°C increase occurring in the winter months. Increases in air temperature are likely to affect the accumulation and melt of snowpack, the extent of lake ice, and the timing of spring ice break up, and result in increased water temperatures. Research from adjacent regions provides some basis for estimating water temperature changes that may result from climate change. Kyle and Brabets (2001) estimated that air temperature increases of 7.2°C to 8.5°C projected for Cook Inlet watersheds by 2100 would be associated with water temperature increases of 1.2°C to 7.1°C. It is important to note that although air temperature can be a useful metric for modeling water temperature, other factors (e.g., quantity, type, and seasonality of precipitation, snow and glacier cover) can also be critical water temperature drivers (Webb and Nobilis 1997, Mohseni and Stefan 1999).

Although we are unable to predict a change in extreme events, changes in precipitation patterns are likely to occur (Salathé 2006, Christensen et al. 2007, Peacock 2012, Markon et al. 2012), with rain-on-snow events becoming more common. The effect of increased rain-on-snow events on the frequency or volume of floods is unclear. Storm patterns also may change, although the increased likelihood of extreme events occurring and potential impacts on flooding are unknown. Changes in the seasonality of precipitation, snowpack, and the timing of snowmelt will likely affect streamflow regimes and may result in water availability changes, particularly in terms of decreased water availability in summer. Based on temperature, precipitation, and evapotranspiration projections, the landscape will likely be warmer and wetter annually; however, due to method limitations we are not able to determine how evapotranspiration will affect water availability on the landscape seasonally (Box 3-4).

3.8.1 Climate Change Projections for the Bristol Bay Region

Across the entire Bristol Bay watershed, average temperature is projected to increase by approximately 4°C by the end of the century (Table 3-5, Figure 3-16), and winter temperature is projected to increase the most (Table 3-5). Similar patterns are projected in the Nushagak and Kvichak River watersheds (Table 3-5).

By the end of the century, precipitation is projected to increase roughly 30% across the Bristol Bay watershed, for a total increase of approximately 250 mm annually (Table 3-6, Figure 3-17). In the Nushagak and Kvichak River watersheds, precipitation is projected to increase roughly 30% as well, for a total increase of approximately 270 mm of precipitation annually (Table 3-6). At both spatial scales, increases in precipitation are expected to occur in all four seasons (Table 3-6). Based on evapotranspiration calculations, annual water surpluses of 144 mm and 165 mm are projected for the Bristol Bay watershed and the Nushagak and Kvichak River watersheds, respectively (Table 3-7, Figure 3-18). Our simulated temperature and precipitation changes based on SNAP (2012) data for the Bristol Bay region are within the range of changes projected by other studies concentrating on Alaska and the Arctic (Christensen et al. 2007, Peacock 2012, Markon et al. 2012).

Table 3-5. Average annual and seasonal air temperature for historical and projected periods across the Bristol Bay watershed and the Nushagak and Kvichak River watersheds. Values were calculated using the SNAP (2012) dataset (Box 3-4). Temperature was calculated as average values over each 30-year period. Number in parentheses equals one standard deviation.

Scale	Season	Historical Temperature (1971–2000) (°C)	Projected Temperature (2017–2099) (°C)	Difference (°C)
Bristol Bay Watershed (Scale 1)	**Annual**	**1** (1)	**5** (1)	**4** (0.2)
	Winter	-8 (2)	-2 (2)	6 (1)
	Spring	0 (1)	4 (1)	4 (0.2)
	Summer	11 (2)	14 (2)	3 (0.07)
	Fall	1 (2)	5 (2)	4 (0.3)
Nushagak and Kvichak River Watersheds (Scale 2)	**Annual**	**1** (1)	**5** (1)	**4** (0.2)
	Winter	-9 (1)	-3 (1)	6 (0.4)
	Spring	0 (1)	4 (1)	3 (0.2)
	Summer	11 (2)	14 (2)	3 (0.05)
	Fall	0 (2)	5 (2)	4 (0.07)

Table 3-6. Average annual and seasonal precipitation for historical and projected periods across the Bristol Bay watershed and the Nushagak and Kvichak River watersheds. Values were calculated using the SNAP (2012) dataset (Box 3-4). Precipitation was calculated as average values over each 30-year time period. Number in parentheses equals one standard deviation.

Scale	Season	Historical Precipitation (1971–2000) (mm)	Projected Precipitation (2017–2099) (mm)	Difference (mm)
Bristol Bay Watershed (Scale 1)	**Annual**	**847** (421)	**1,095** (512)	**248** (104)
	Winter	177 (121)	229 (143)	52 (27)
	Spring	150 (91)	196 (112)	45 (25)
	Summer	234 (97)	303 (117)	69 (25)
	Fall	286 (141)	367 (170)	81 (34)
Nushagak and Kvichak River Watersheds (Scale 2)	**Annual**	**795** (336)	**1,062** (430)	**267** (95)
	Winter	160 (79)	215 (97)	55 (21)
	Spring	138 (67)	189 (90)	51 (23)
	Summer	226 (84)	300 (107)	75 (24)
	Fall	271 (123)	357 (152)	86 (32)

Table 3-7. Average annual water surplus for historical and projected periods across the Bristol Bay watershed and the Nushagak and Kvichak River watersheds. Values were calculated using the SNAP (2012) dataset (Box 3-4). Number in parentheses equals one standard deviation.

Scale	Historical Surplus (1971–2000) (mm)	Projected Surplus (2017–2099) (mm)	Difference (mm)
Bristol Bay Watershed (Scale 1)	400 (441)	544 (534)	144 (106)
Nushagak and Kvichak River Watershed (Scale 2)	341 (359)	506 (456)	165 (99)

Figure 3-16. Mean annual temperature across the Bristol Bay watershed under (A) historical conditions (1971 to 2000) and (B) the A2 emissions scenario (2071 to 2099), and (C) the temperature change between these two climate scenarios (SNAP 2012). See Box 3-4 for additional details.

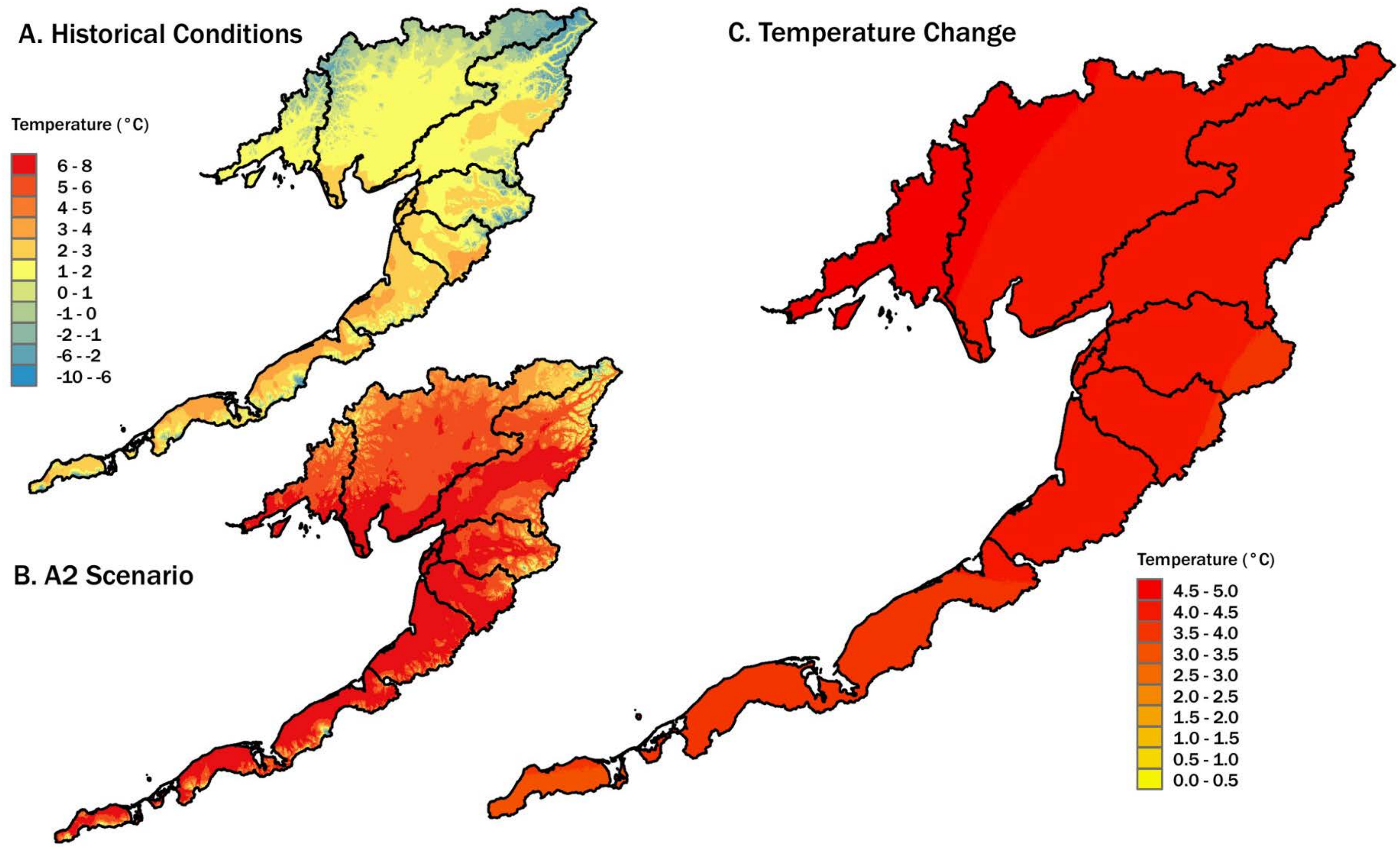


Figure 3-17. Mean annual precipitation across the Bristol Bay watershed under (A) historical conditions (1971 to 2000) and (B) the A2 emissions scenario (2071 to 2099), and (C) the precipitation change between these two climate scenarios (SNAP 2012). See Box 3-4 for additional details.

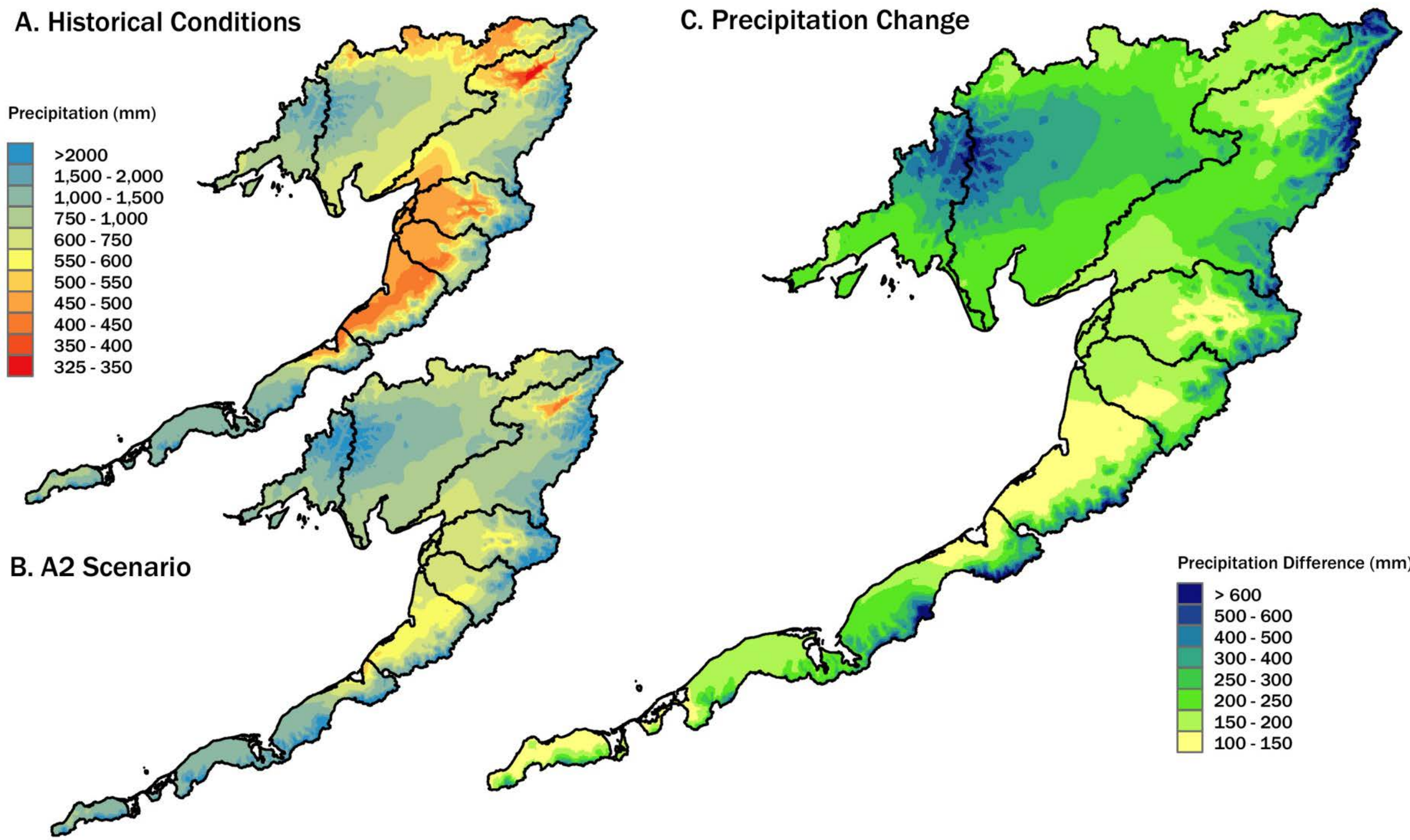
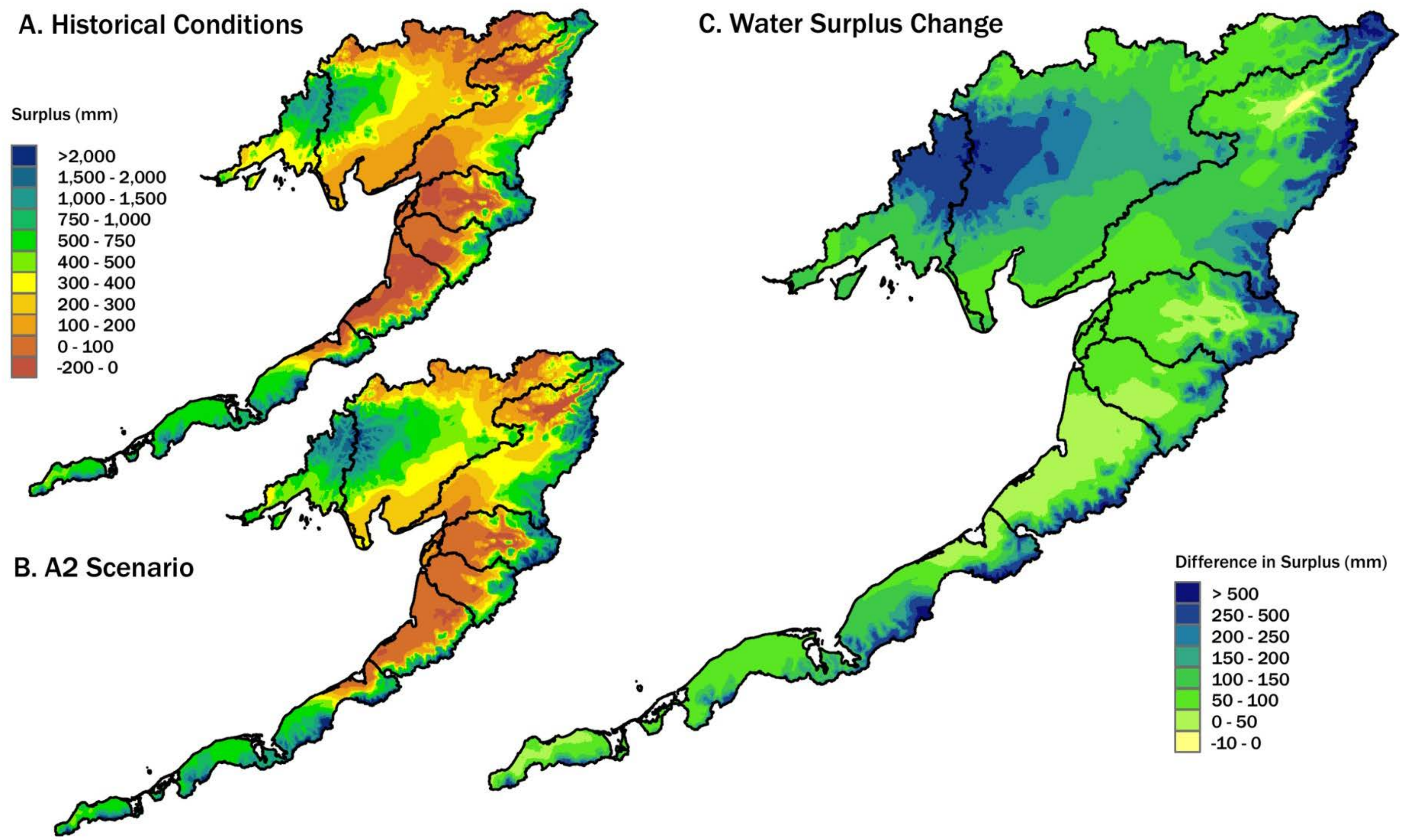


Figure 3-18. Mean annual water surplus (precipitation minus evapotranspiration) across the Bristol Bay watershed under (A) historical conditions (1971 to 2000) and (B) the A2 emissions scenario (2071 to 2099), and (C) the water surplus change between these two climate scenarios (SNAP 2012). See Box 3-4 for description of surplus calculations.



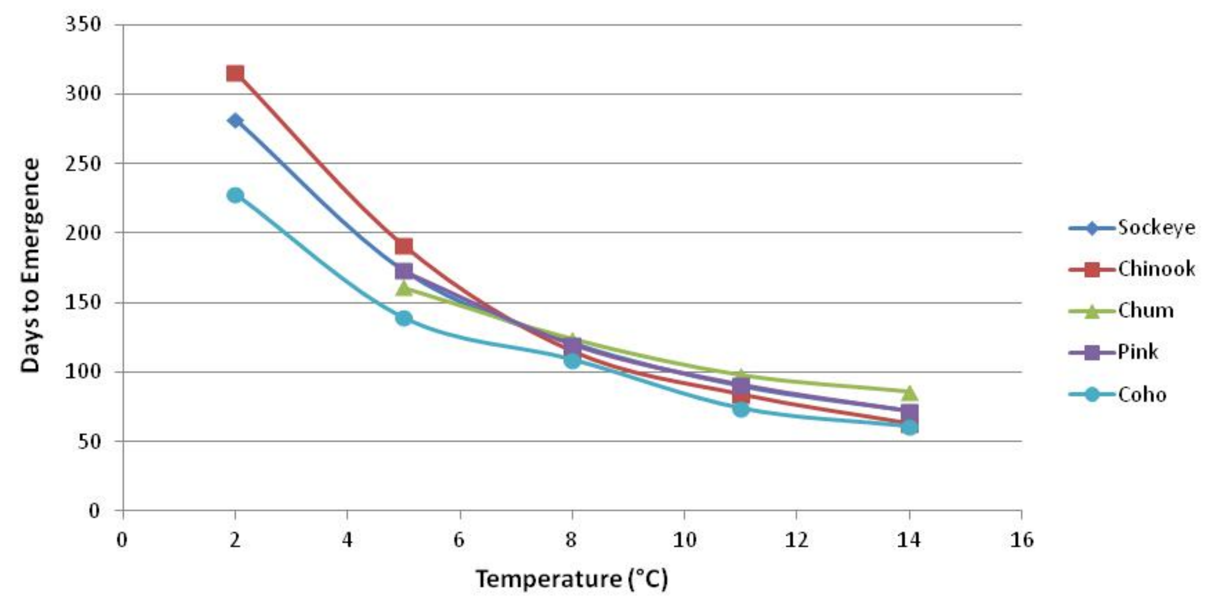
3.8.2 Potential Climate Change Effects

There are likely to be hydrological impacts associated with projected changes in temperature, precipitation, and evapotranspiration in the Bristol Bay watershed, including changes in the magnitude and timing of streamflow that are likely to affect salmon habitat and populations. When temperature increases in freshwater environments, community structure, habitat, and salmon populations can be affected (Eaton and Scheller 1996, Hauer et al. 1997). With warmer temperatures and changes in the type, timing, and amount of precipitation, there likely will be changes in snowpack, a shift in the timing of spring snowmelt, and changes in the type of precipitation falling (Barnett et al. 2005). With these changes, there will be alterations to both the magnitude and timing of the natural streamflow regime and a likely decline in seasonal water availability, mirroring already observed changes in other systems such as the Pacific Northwest (Mote et al. 2003).

These hydrologic flow regime changes may affect salmon populations during spawning and smolt migrations, and can scour streambeds leading to the loss of salmon eggs (Lisle 1989, Montgomery et al. 1996, Steen and Quinn 1999, Mote et al. 2003, Lawson et al. 2004, Stewart et al. 2004). Changes in hydrology are likely to affect existing habitat via changes in water volume and velocity along with channel forms, which may lead to declines in habitat availability for spawning and rearing salmon populations. Changes to baseflow, depending on groundwater and surface water interactions, are likely to affect the amount of wetlands in the Bristol Bay watershed, in that wetlands are likely to decrease under drier baseflow conditions. Although we are unable to predict whether baseflow will increase or decrease, any changes in baseflow will likely affect water temperature (in addition to the direct effects of increased air temperature on water temperature).

Both the hydrology and water temperature of freshwater systems affect critical life stages of salmonid species. Furthermore, these hydrological changes are likely to have different effects on salmon populations depending on the amount of time they spend rearing in freshwater habitats, their life stage, and their ability to adapt to changes in environmental conditions. Pink and chum salmon are likely to be affected by temperature increases early in egg incubation, which can affect timing of emergence, migration to the ocean, and potential mismatch in the timing of peak food abundance in the marine environment (Bryant 2009). For example, the average migration time for one population of pink salmon in southeast Alaska now occurs nearly 2 weeks earlier than it did 40 years ago (Kovach et al. 2012). For sockeye salmon that typically rear in fresh water for 1 to 2 years, temperature increases may affect life-stage timing, including spawning and fry emergence, as well as the growth and survival of lake-rearing fry (Healey 2011, Martins et al. 2012). Across all five Pacific salmon species, time to fry emergence decreases as water temperature increases (Figure 3-19); thus, warmer winters may result in earlier fry emergence.

Figure 3-19. Relationship between time from fertilization to emergence and temperature for the five Pacific salmon species. Data are from Quinn 2005.



Changes in precipitation and hydrology also may affect access to lakes and spawning locations, and high-intensity rainfall may increase sedimentation in spawning streams and rearing lakes for sockeye salmon (Bryant 2009). Rich et al. (2009) hypothesized that warmer temperature was a factor in poor sockeye salmon recruitment in the Kvichak River watershed. For Chinook salmon, increases in temperature are likely to affect incubation and fry emergence (Beer and Anderson 2001), which may affect growth, survival, and timing of migration to the ocean (Heming et al. 1982, Taylor 1990, Berggren and Filardo 1993). Coho salmon incubation and timing of emergence are also affected by increases in temperature (Tang et al. 1987).

Populations of Pacific salmon species are likely to respond and adapt to changes in temperature, precipitation, and hydrology in different ways, and the geographic location of populations is likely to affect their ability to adapt to these changes. Studies have predicted that the reproductive success of salmon populations in Washington is likely to decline over the next century (Battin et al. 2007, Mantua et al. 2010), and freshwater temperature increases in the Fraser River will negatively affect growth and survival of sockeye salmon at all life stages (Healey 2011). The genetic and life history diversity within and among the Bristol Bay Pacific salmon populations (Section 5.2.4) will likely be crucial for maintaining the resiliency of the region's salmon stocks under a future environment characterized by climate change and increased anthropogenic stressors (Hilborn et al. 2003, Schindler et al. 2010, Rogers and Schindler 2011).